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Transition pathways for a UK low carbon electricity system: Comparing scenarios and technology implications

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16 December 2013

Realising Transition Pathways

Whole systems analysis for a UK more electric low carbon energy future



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Realising Transition Pathways

‘Realising Transition Pathways’ (RTP) is a UK Consortium of engineers, social scientists and policy analysts. The consortium is managed by Professor Geoffrey Hammond of the University of Bath and Professor Peter Pearson of Cardiff University (Co-Leaders). It includes research teams from nine British university institutions: the Universities of Bath, Cardiff, East Anglia, Leeds, Loughborough, Strathclyde, and Surrey, as well as Imperial College London and University College London. The RTP Project [www.realisingtransitionpathways.org.uk] commenced in May 2012 and is sponsored by the ‘Engineering and Physical Sciences Research Council’ (EPSRC: Grant EP/K005316/1). It is a renewal and development of the earlier ‘Transition Pathways’ (TP) project, which was initially established in 2008 with the joint sponsorship of E.ON UK (the electricity generator) and the EPSRC. This project addressed the challenge of the so-called energy ‘trilemma’: the simultaneous delivery of low carbon, secure, and affordable energy services for the electricity sector. It developed and applied a variety of tools and approaches to analyse the technical feasibility, environmental impacts, economic consequences, and social acceptability of three ‘transition pathways’ towards a UK low carbon electricity system. These pathways explore the roles of market, government and civil society actors in the governance of a low carbon energy transition.

The research within the RTP Project seeks to explore further the constraints and opportunities in realising a low carbon UK energy sector, including those stemming from European developments. This project includes studies on the horizon scanning of innovative energy technologies over the period to 2050, the feasibility of demand responses, uncertainties in economic analysis, the estimation of investment costs of the different pathways, and the implications of markets for investment decisions about energy technologies. Further work is being undertaken on conceptualising, mapping and analysing ‘actor dynamics’ in the contemporary UK electricity sector, historical transitions and case studies, integrated energy networks modelling and evaluation, and ‘whole systems’ energy and environmental appraisal of low carbon technologies and pathways. The consortium is also developing their initial work on branching points on pathways, in order to identify and explore other potential branching points on the core transition pathways.

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1. Introduction

This paper compares the features and technology implications of a set of transition pathways for a UK low carbon electricity system to 2050 with key scenarios produced by the UK government for meeting the UK's 80% greenhouse gas emissions reduction target by 2050. This aims to provide an overview of how different framings and assumptions on demand reduction and generation mix can lead to significantly diverse low carbon futures (cf. Trutnevyte and Strachan, 2013). More detailed discussion of the framing assumptions, demand side and generation and network implications of the transition pathways can be found in the papers by the project team (Hammond and Pearson, 2013; Foxon, 2013; Barton et al., 2013; Barnacle et al., 2013). Further considerations on the implications of the pathways for government, business and civil society in the context of recent UK energy policy developments is given in Foxon and Pearson (2013). This paper aims to inform debate on the technical feasibility and social acceptability of the pathways and scenarios in relation to how decarbonisation of the UK electricity system can contribute to meeting the UK's energy and carbon reduction goals. However, the paper does not attempt to draw conclusions on the role or desirability of any particular technology or pathway.

The UK has set itself on a transition to a low carbon economy and society, through the imposition of a goal of reducing the UK's greenhouse gas emissions by 80% by 2050 and creation of an institutional framework relating to this goal, under the 2008 Climate Change Act, which was passed with agreement of all major political parties. As generation of electricity constitutes a significant proportion of UK greenhouse gases, and technological options exist for the use of low carbon electricity for heating and transport as well as other energy services, much attention has been given to long-term scenarios and pathways for the reduction of carbon emissions from electricity. This type of pathway and scenario analysis is useful to enable actors to reflect on how current energy system decision making relates to the potential for achieving long-term energy and carbon reduction goals (Hughes and Strachan, 2010; Hughes et al., 2013). In order to do this, it is helpful to set out the features and technology implications of different pathways and scenarios. This paper does this by comparing a set of low carbon electricity pathways developed under a research project supported by Research Councils UK and the integrated energy company E.On UK¹ with 'official' pathways developed by the UK Department for Energy and Climate Change (DECC) in HM Government's Carbon Plan (HM Government, 2011).

The low carbon Transition Pathways were developed by the authors and colleagues (Hammond and Pearson, 2013; Foxon, 2013) to examine the influence of different governance arrangements on potential pathways towards the 80% reduction target by 2050. These pathways focus on the electricity sector, including the potential for increasing use of low carbon electricity for heating and transport. This follows the main scenarios developed by the Committee on Climate Change (CCC) and DECC, which also focussed on low carbon electrification as the key first step in the transformation of the UK energy system needed to meet the 80% target by 2050². However, unlike these scenarios, the Transition

¹ The responsibility for the content of the pathways remains with the authors, and should not be taken to represent the views of any funder of the research.

² Note that some researchers have argued that the UK needs to focus on reducing cumulative emissions and to achieve higher carbon reductions by 2050, in order for the UK to take its fair share of the global reductions needed to meet a maximum 2°C temperature rise (Anderson and Bows, 2012).

pathways were developed by starting from narrative storylines as to the potential consequences of different governance framings, drawing on interviews and workshops with stakeholders³ and analysis of historical analogies (Arapostathis et al., 2013). An iterative process of technical elaboration between social science and engineering researchers, informed by energy system modelling (Barton et al., 2013; Barnacle et al., 2013), was then followed to produce a quantification of the narrative for each pathway, as described in Foxon (2013). This provides a way of examining the potential influence of qualitative social and institutional changes on the development of low carbon pathways, as well as providing a basis for more detailed technical and economic analyses of the pathways. However, it is important to compare the final quantified pathways with the main pathways developed by DECC.

The paper is structured as follows. Sections 2 and 3 review the demand and generation projections for the low carbon transition pathways. Section 4 reviews the future scenarios in the UK Government's Carbon Plan. Section 5 provides a comparison of the pathways and scenarios. Section 6 examines technology implications of the pathways and scenarios. Section 7 assesses the greenhouse gas emissions projections for the transition pathways, before conclusions in section 8.

³ See website www.lowcarbonpathways.org.uk for reports and presentations from project workshops.

2. Low Carbon Transition Pathways – demand projections

The Transitions Pathways study approaches pathways from a governance perspective, and technology scenarios are produced under those perspectives. Foxon (2013) describes three pathways, based on different dominant governance framings:

- 1) The *Market Rules* pathway is based on governance system similar to that of today, with a liberalised and privatised electricity and gas sector. Under this pathway, the dominant logic is that of the market: the best way to achieve the objectives is for government to set general high-level policy targets and the actors – in this case primarily large energy companies – deliver these.
- 2) The *Central Coordination* pathway is a world in which the government comes to the conclusion that meeting security of supply, affordability and emissions objectives will require direct intervention. This involves a government agency forming supply contracts for different low-carbon technology types to develop areas which are of importance to both the UK grid and in the strategic interest of the UK economy. In addition, public/private partnerships develop technology. This leads to strong advances in marine renewables, Carbon Capture and Storage (CCS) and electric vehicles. On the demand side, incentives are provided for household energy efficiency, although electrification of heating and transport drive up electricity demand.
- 3) The *Thousand Flowers* pathway envisages a low-carbon transition which is led by civil society. This bottom-up approach focuses on decentralised solutions to energy problems and has at its heart a society which is aware and informed on environmental themes and takes a proactive approach. Energy service companies (ESCOs) also emerge, which have incentives more aligned with energy efficiency improvements which aids the transition to a low-carbon economy.

In these pathways, actors move towards achieving the 80% carbon emissions reduction target by 2050, though the extent to which the resulting emissions reductions in the electricity sector contribute to meeting this target depends on projections of the effectiveness of these technologies achieving reductions, particularly when life cycle impacts are included (see Hammond et al., 2013).

The starting point for the quantification of these pathways is the projection of annual electricity demand by sector from 2010 to 2050. This is shown in Figures 2.1-2.3.

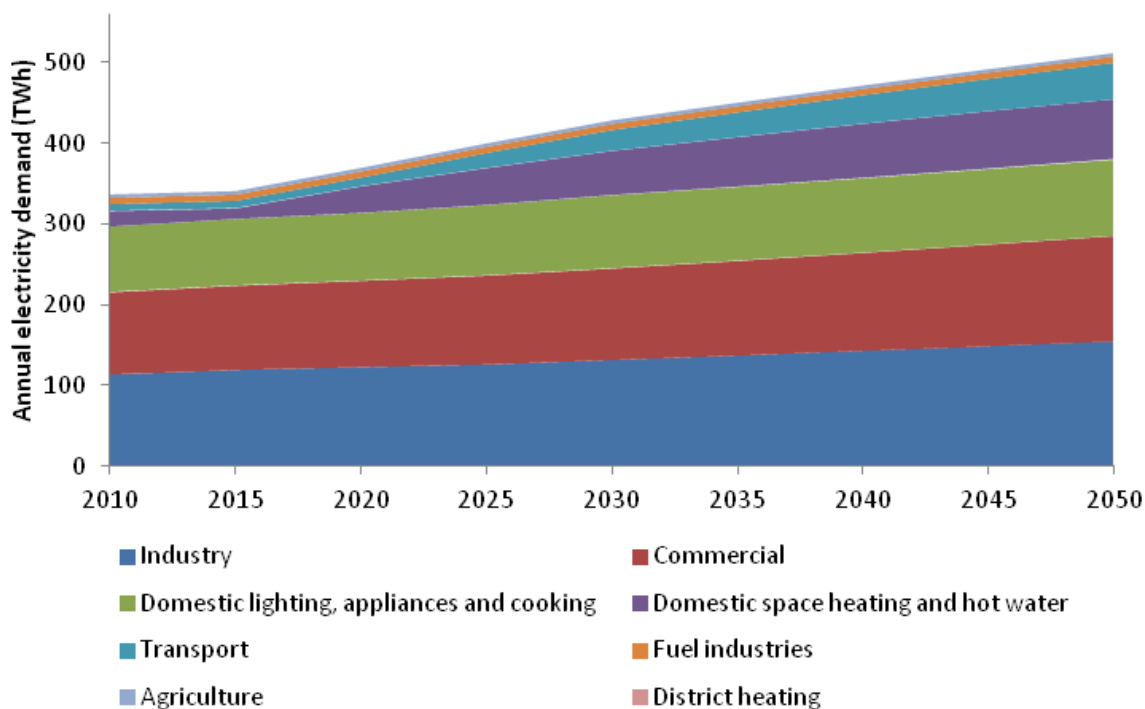


Figure 2.1. Annual electricity demand (TWh) in *Market Rules* pathway 2010-2050 (based on Barton et al. (2013))

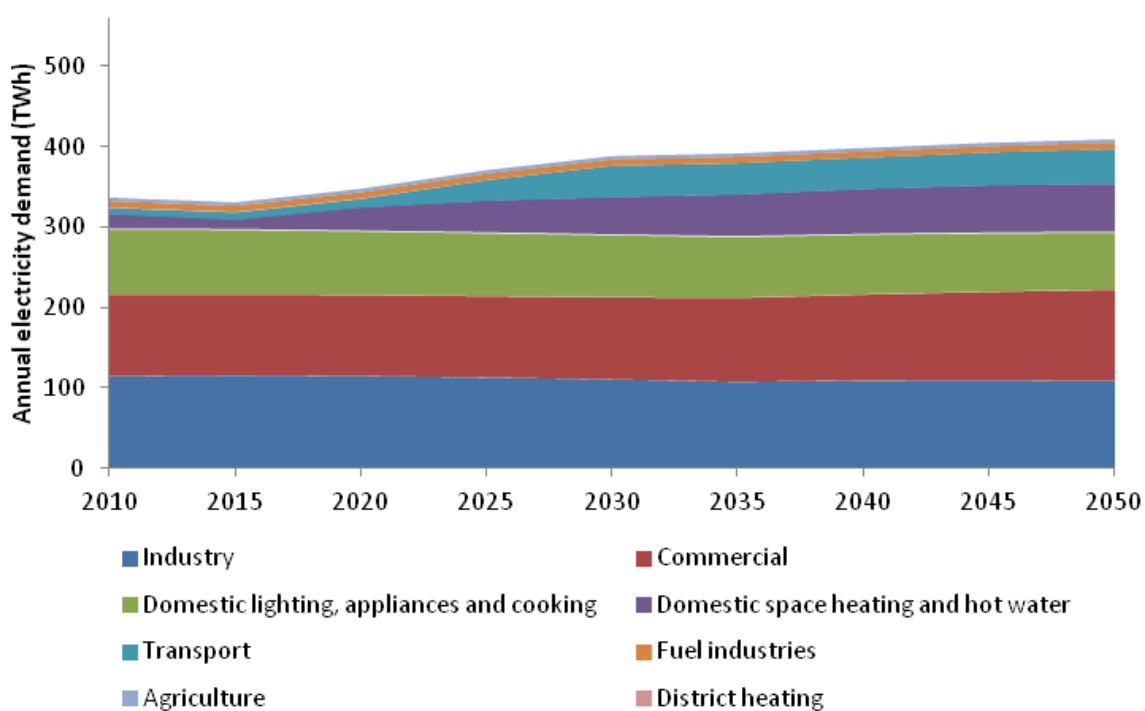


Figure 2.2. Annual electricity demand (TWh) in *Central Co-ordination* pathway 2010-2050 (based on Barton et al. (2013))

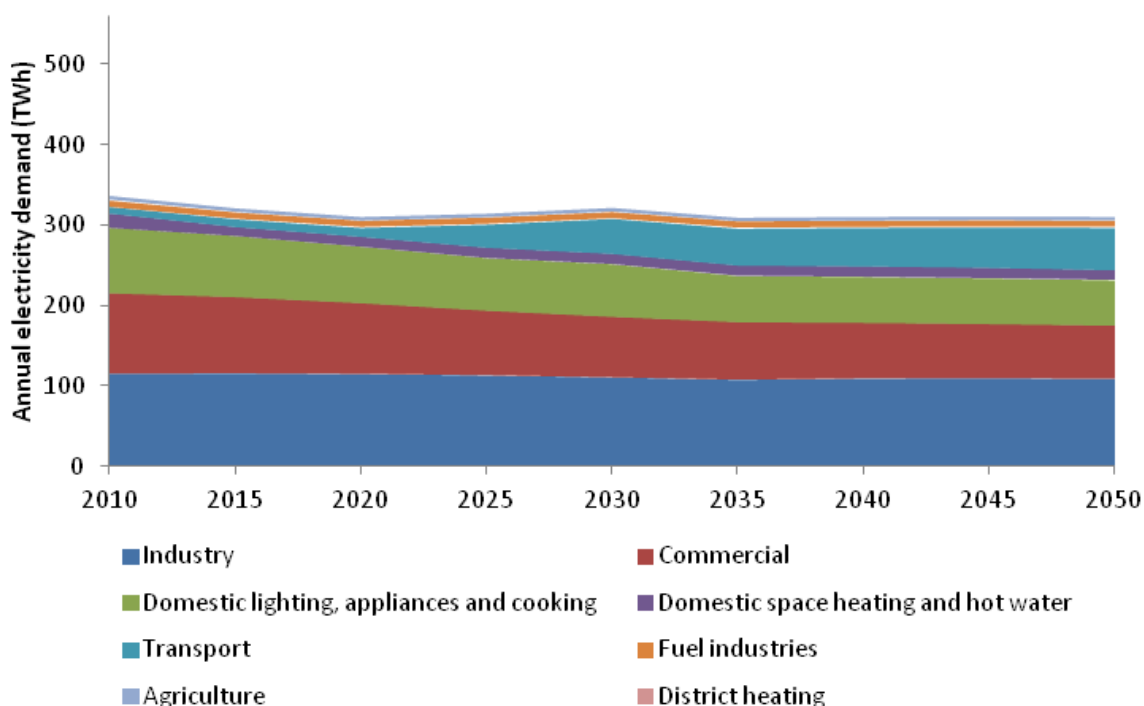


Figure 2.3. Annual electricity demand (TWh) in *Thousand Flowers* pathway 2010-2050 (based on Barton et al. (2013))

In the *Market Rules* pathway, annual electricity demand rises from 337 TWh in 2010 to 512 TWh in 2050, due to increasing use of electricity for industry, commercial, transport and domestic space heating and hot water. This means that the electricity system needs to provide 50% more output by 2050 than it currently does, requiring significant expansion of low-carbon generation beyond just replacing existing capacity.

In the *Central Co-ordination* pathway, annual electricity demand rises from 337 TWh in 2010 to 410 TWh in 2050. This pathway sees electricity demand rising and then levelling off from 2030 onwards, due to increasing use of electricity for transport and domestic space heating and hot water, but with higher rates of energy efficiency improvements in the domestic sector, and a smaller, highly efficient industrial sector with lower levels of output. This would imply that some energy-intensive UK production has moved to other countries, increasing the UK consumption of goods produced abroad, implying that UK carbon emissions calculated on a consumption basis would continue to diverge from those on a production basis (see Barrett et al., 2013).

In the *Thousand Flowers* pathway, annual electricity demand falls from 337 TWh in 2010 to 310 TWh in 2050. Despite similar levels of electrification of transport to the other pathways, electricity demand falls due to even higher rates of energy efficiency improvements in the domestic and commercial sectors, and a small, highly efficient industrial sector with low levels of output. In this pathway, a large proportion of domestic space heating and hot water demand is met by renewable (biogas) community-scale and micro- CHP systems rather than electric heating systems, helping to reduce electricity demand. In addition, the power generated by these local scale CHP systems replaces a significant proportion of centralised electricity supply, as discussed below.

Note that in all pathways, a significant amount of energy is used in industry and commerce for space heating and water heating. The provision of this heat is mostly via the same technologies as in the domestic sector of each pathway but often on a larger scale. Thus in the *Market Rules* and *Central Coordination* pathways, an increasing amount of electricity is used in heat pumps in the industrial and commercial sectors, as shown in Table 2.1.

Pathway	Market Rules		Central Coordination		Thousand Flowers	
Year	2010	2050	2010	2050	2010	2050
Total Electricity for Heat & Hot Water (TWh)	23	108	22	94	22	18
Domestic Electricity for Heat & Hot Water (TWh)	19	73	19	60	18	13
Industrial & Commercial Electricity for Heat & Hot Water (TWh)	3	35	3	34	4	6

Table 2.1. Electricity used for space heating and hot water in domestic, industry and commerce sectors

Thus, the increased demand for electricity for heating and hot water in the *Market Rules* and *Central Coordination* pathways, in addition to the additional demand due to electrification of transport, leads to a significant increase in total final electricity demand in these pathways. On the contrary, in the *Thousand Flowers* pathway, the total final electricity demand remains stable up to 2050, as the increase in transport electricity demand is offset by reductions in demand to energy efficiency improvements, and there is no increase in electricity demand for heating and hot water, due to the expansion of community-scale renewable CHP.

3. Low Carbon Transition Pathways – supply projections

In the Transition Pathways study, these demand projections for the three pathways are met by rising levels of low carbon electricity generation, including different generation capacities of renewables, nuclear power and coal and gas with carbon capture and storage (CCS or sequestration), operating at different capacity factors. The generation capacity for each pathway from 2010 to 2050 is shown in Figures 3.1-3.3.

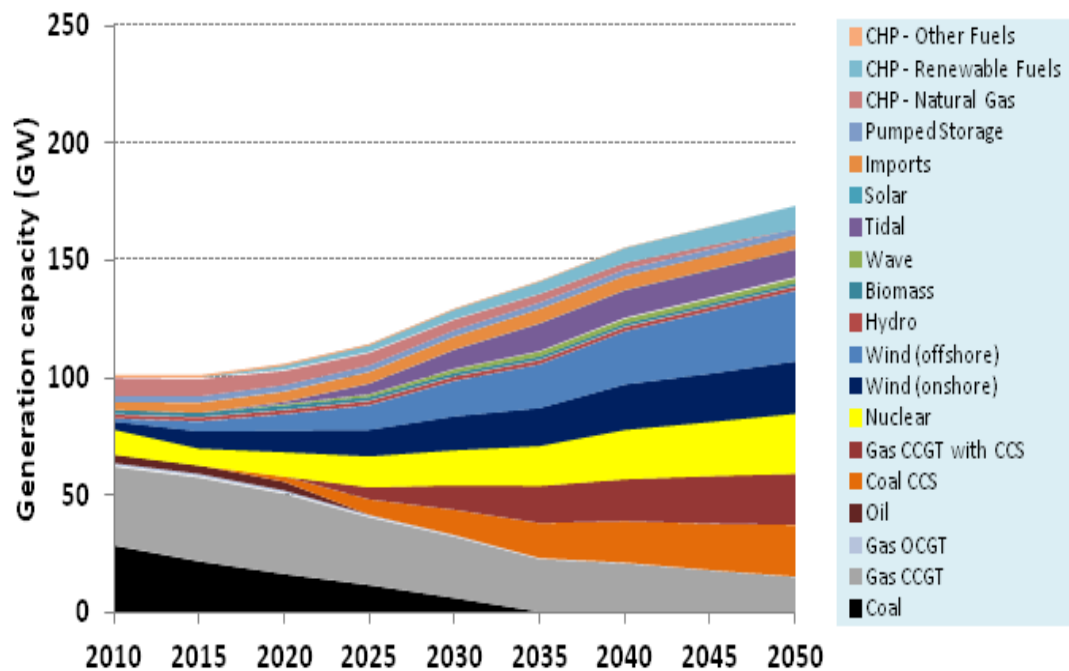


Figure 3.1. Generation capacity in *Market Rules* pathway (based on Barnacle et al. (2013))

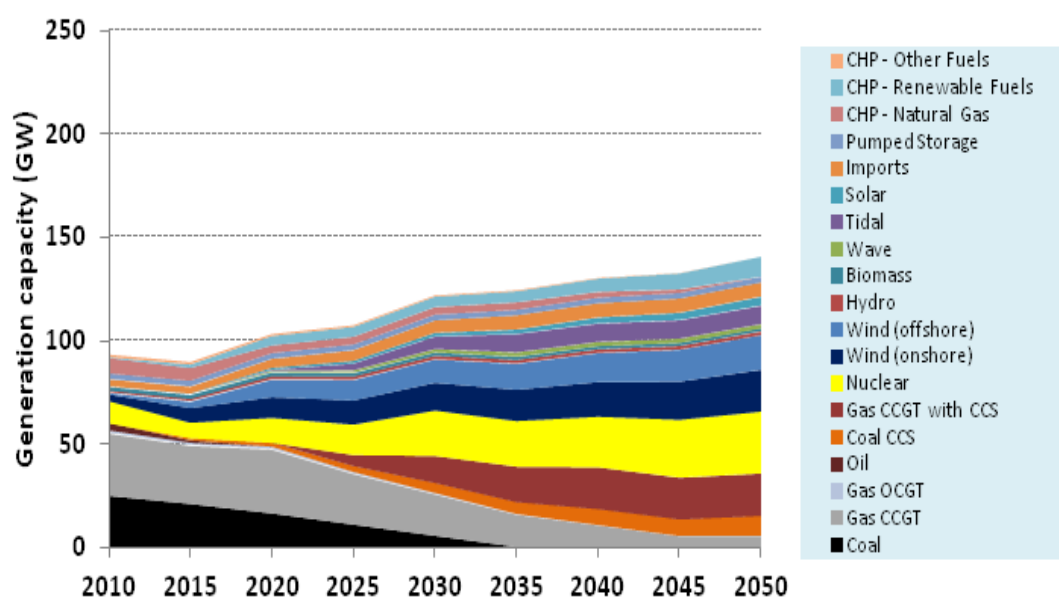


Figure 3.2. Generation capacity in *Central Co-ordination* pathway (based on Barnacle et al. (2013))

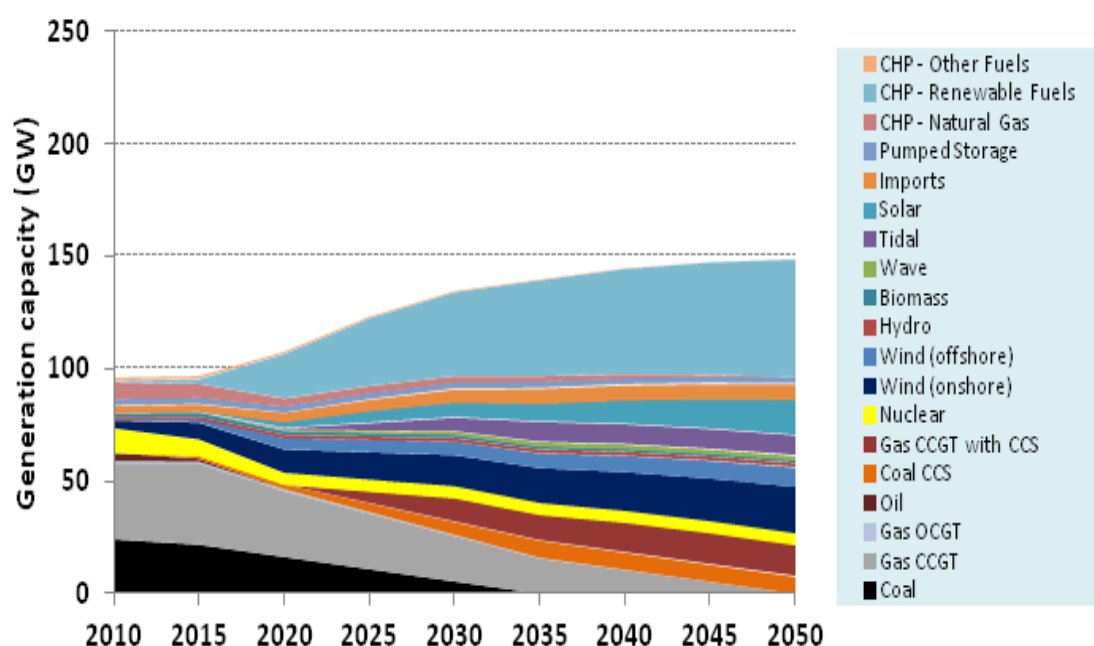


Figure 3.3. Generation capacity in *Thousand Flowers* pathway (based on Barnacle et al. (2013))

Timelines

In 2010, the UK had around 95 GW of electricity generation capacity, including 29 GW of coal and dual fuel generation, 33 GW of gas-fired generation, 11 GW of nuclear power, 9 GW of renewable generation and 6 GW of combined heat and power (CHP) cogeneration. In the *Market Rules* pathway, investment occurs in all three main types of low-carbon generation, driven by a high carbon price. Significant amounts of capacity come on stream in the 2020s, so that, by 2030, there are 21 GW of coal and gas with carbon capture and storage (CCS), 15 GW of nuclear power and 47 GW of renewables (47 GW), giving a total capacity of 130 GW by 2030. Subsequent deployment leads to further increases in capacity in order to meet rising electricity demand, particularly from industry and electrification of heating and transport, over following decades. By 2050, this results in a total of 168 GW of capacity, including 44 GW of coal and gas generation with CCS, 26 GW of nuclear power, and 80 GW of renewable capacity, principally onshore (23 GW) and offshore (30 GW) wind, tidal power (12 GW) and renewable CHP (9 GW). This provides a total supply of 539 TWh in 2050.

In the *Central Co-ordination* pathway, there is a similar investment in all types of low-carbon generation capacity in the 2020s, co-ordinated by a Strategic Energy Agency. This leads to a total of 122 GW in 2030, though with high levels of nuclear power (22 GW), and slightly lower levels of coal and gas with CCS (18 GW) and renewables (43 GW). Despite the subsequent levelling off of demand in this pathway, further deployment needs to an increase in capacity to a total of 151 GW by 2050, of which the largest single contribution comes from nuclear power (30 GW). There is a similar contribution (30 GW) coal and gas fired generation with CCS, but this operates at a lower capacity factor (36%), as it partly provides back-up to intermittent renewables. There is a total of 65 GW of renewable generation, of which the largest contributions are from onshore (21 GW) and offshore (17 GW) wind. This provides a total supply of 427 TWh in 2050.

In the *Thousand Flowers* pathway, action by community groups and local and regional energy service companies (ESCOs) leads to a significant expansion of community- and micro-scale renewable CHP installed from 2020 onwards, reaching a total of 37 GW by 2030. The total capacity of 149 GW by 2050 is similar to that of *Central Co-ordination*, but the majority of this is made up of renewable generation (112 GW). As noted above, a significant proportion of demand is met by local scale renewables, reducing the need for centralised electricity supply. The largest single contribution to generation comes from renewable (biogas) community-scale and micro- CHP systems (44 GW), followed by onshore wind (21 GW), solar PV (16 GW) and offshore wind (8 GW). There is some investment in other low carbon generation technologies in earlier periods, resulting in 22 GW of coal and gas with CCS and 5 GW of nuclear capacity by 2050. This provides a total supply of 313 TWh in 2050.

Summary

Hence, in all three pathways, generation capacity increases substantially by 2050, but the generation mixes are markedly different between the pathways. In the *Market Rules* and *Central Co-ordination* pathways, coal and gas fired generation with CCS, nuclear power and onshore and offshore wind all make significant contributions to capacity, required to provide the output to meet the rising electricity demand in these pathways. In the civil society-led *Thousand Flowers* pathway, there is much less investment in these large centralised generation options, and instead, a significant expansion of more local generation from renewable (biogas) community-scale and micro- CHP, onshore wind and solar PV.

4. UK Carbon Plan pathways

The Carbon Plan (HM Government, 2011) is the most recent statement by the UK Government of the range of measures and incentives that it has already or intends to put in place, to ensure that the UK is on track to meet the target of reducing its greenhouse gas emissions by 80% by 2050, as required by the Climate Change Act (2008). A foreword to the Carbon Plan, signed by the Prime Minister and the Deputy Prime Minister, states that “Even in these tough times, moving to a low carbon economy is the right thing to do, for our economy, our society and the planet” (HM Government, 2011, Foreword). Though the Plan addresses the whole of the UK economy, the main measures relate to the energy sector. The Plan also seeks to address the so-called ‘trilemma’ of energy policy: “to make the transition to a low carbon economy, whilst maintaining energy security and minimising costs to consumers, particularly those in poorer households” (HM Government, 2011, p.3).

The main focus of the Carbon Plan is the additional measures needed to meet the fourth carbon budget, covering 2023-27, which was set into law 12 years in advance, as required under the Climate Change Act, following the recommendation for the budget level by the Committee on Climate Change (CCC, 2011). This requires UK greenhouse gas emissions to be reduced by 50% below 1990 levels by 2023-27, an additional 29% below 2009 levels. The main measures include the Green Deal, a scheme for households to finance energy efficiency improvements at no upfront cost which began operating in January 2013 (DECC, 2010b), and the Electricity Market Reform programme for stimulating investment in low carbon electricity generation (DECC, 2012a). The latter is embodied in the Energy Bill going through the UK Parliament in 2012-13, though the first negotiations are already underway with energy company EDF to provide a guaranteed ‘strike price’ for the first two new nuclear power stations, planned to be built at Hinkley Point, under the new ‘Contract for Difference Feed-in Tariffs’, a key part of the reforms⁴. As noted, the key challenge for the UK government will be to balance these incentives for investment in low carbon generation, including renewables, nuclear and demonstration CCS projects with ensuring energy security and maintaining affordability of energy to consumers.

This is linked to the challenge of ensuring sufficient progress to keep the UK on track to meet its 80% reduction target by 2050, whilst limiting the additional costs both to the Treasury and those costs passed on to consumers in the short- to medium-term. This is very challenging in the face of a number of uncertainties, including future levels of energy service demand - which depend on uptake of energy efficiency measures and end-use technologies and levels of economic activity - and the technical and economic feasibility and acceptability of a range of low carbon energy options, particularly for electricity generation. To this end, the Carbon Plan explores four 2050 futures, which are potential pathways or scenarios for meeting the 80% reduction target by 2050. The first is based on a ‘core’ simulation run of the MARKAL cost-optimising energy system model and the three other scenarios were developed using the DECC 2050 calculator tool. This section sets out the electricity demand and supply projections in these scenarios and in the next section compare these to those of

⁴ On 21 October 2013, the UK Government announced an agreement with French energy company EDF and its Chinese energy company partners to provide support for the building of a new 2 reactor 3.2 GW nuclear power station at Hinkley Point in South-West England, guaranteeing an index-linked price of at least £89.50 for each MWh generated for 35 years, <https://www.gov.uk/government/news/hinkley-point-c>

the transition pathways to 2050. The projected electricity demand and generation capacity of the Carbon Plan pathways are shown in Figures 4.1-4.7.

4.1. Core MARKAL scenario

Overall trends

In the core MARKAL scenario, the cost-optimised parameterisation includes a sharp reduction in overall per capita energy demand, thanks to end-use energy efficiency improvements and switch to more efficient electric heating and vehicles. However, as a result, electricity demand rises by 46% to 433 TWh by 2050 (see Figure 4.1), and almost all of this needs to be met by low carbon generation sources. Under the core MARKAL (updated MARKAL 3.26) scenario, by 2050, capacity rises to a total of 112 GW (see figure 4.2), including 31 GW of nuclear, 25 GW of coal, biomass and gas generation with carbon sequestration, and 49 GW of renewable generation, with 7.5 GW of standby/peaking gas capacity, providing a total of 560 TWh of supply, of which 89 TWh is exported. This is driven by the expansion of the use of low carbon electricity in transport for electric vehicles and in heating via air- and ground-source heat pumps, as well as for domestic and industrial power and lighting services. Note that this scenario implies an overall increase in the average capacity factor of electricity generation from 43% in 2010 to 58% in 2050, thanks partly due to a projected capacity factor of 80% for new nuclear power stations.

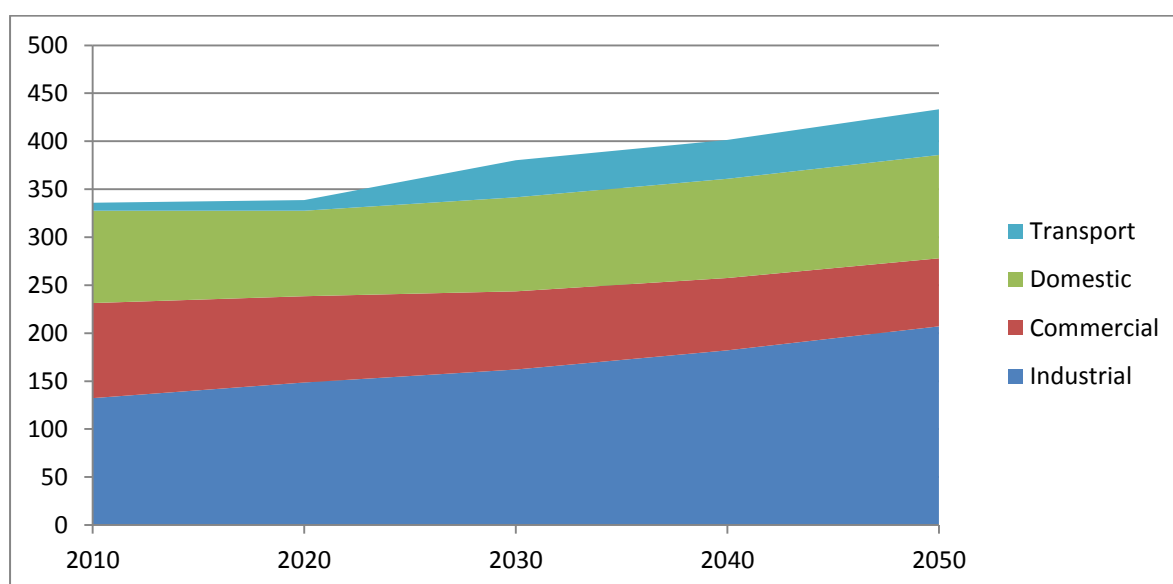


Figure 4.1. Annual electricity demand (TWh) in core MARKAL scenario 2010-2050 (based on HM Government, 2011)

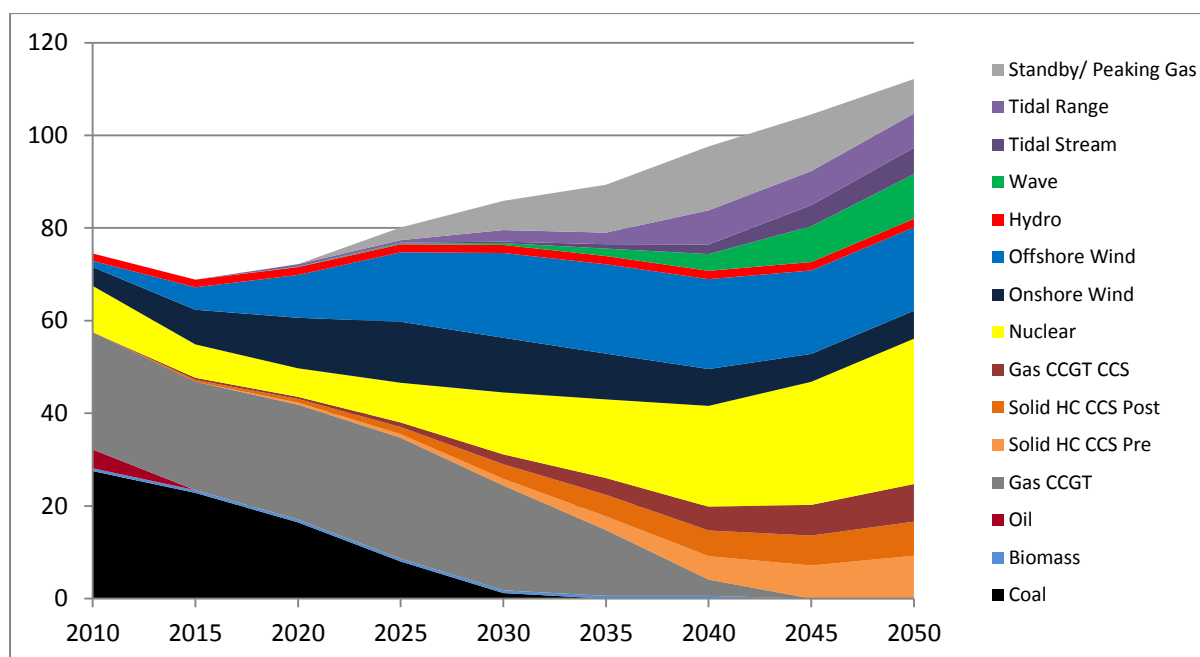


Figure 4.2. Generation capacity (GW) in core *MARKAL* scenario 2010-2050 (based on HM Government, 2011)

Timeline

In this scenario, there is a rapid expansion of onshore and offshore wind to 2030 to replace declining coal capacity, though there remains significant gas CCGT capacity to 2030. Nuclear power capacity expands rapidly after 2030 to become three times as large as current nuclear capacity by 2050. There is a slower expansion of solid hydrocarbons (roughly equal coal and biomass) with pre- and post-combustion CCS, and gas (roughly equal natural gas and biogas) CCGT with CCS after 2030. There are significant contributions after 2030 from offshore renewables, including tidal range, tidal stream and wave power, and a maintained capacity of offshore wind, though the amount of onshore wind reduces (see Table 4.1).

	2010	2020	2030	2040	2050	Description
<i>Coal</i>	14	8	1	0	0	2GW plant
<i>Biomass</i>	12	12	12	12	0	50MW Plant
<i>Gas CCGT</i>	26	24	24	8	0	1GW plant
<i>Solid HC CCS Pre Comb</i>	0	0	1	4	8	1.2 GW locations
<i>Solid HC CCS Post Comb</i>	0	1	3	5	6	1.2 GW locations
<i>Gas CCGT with CCS</i>	0	0	2	4	7	1.2 GW locations
<i>Nuclear</i>	6	4	8	14	20	1.5GW plant
<i>Wind (onshore)</i>	1623	4363	4723	3183	2413	2.5 MW Turbines
<i>Wind (offshore)</i>	232	1592	3154	3345	3103	5.8 MW Turbines
<i>Hydro</i>	16	17	18	18	19	100 MW Sites
<i>Wave</i>	0	54	268	2,410	6,427	1.5 MW Machines
<i>Tidal Stream</i>	1	17	152	1037	2854	Approximate number of 1.2MW Seagen devices
<i>Tidal Range</i>	0	2	10	31	31	Approximate number of 240 MW tidal range sites
<i>Standby/Peak Gas</i>	0	0	3	7	4	2 GW Plant

Table 4.1. Number of plants required to meet installed capacity in core MARKAL scenario

4.2. 'Higher renewables, more energy efficiency' future

Overall trends

In this scenario there are significant improvements in energy efficiency in homes and industry. However, there is also a high degree of electrification in transportation, space heating and hot water, and industry. This leads to a 45 per cent increase in electricity-demand from 2010 to a value of 490 TWh in 2050 (Figure 4.3).

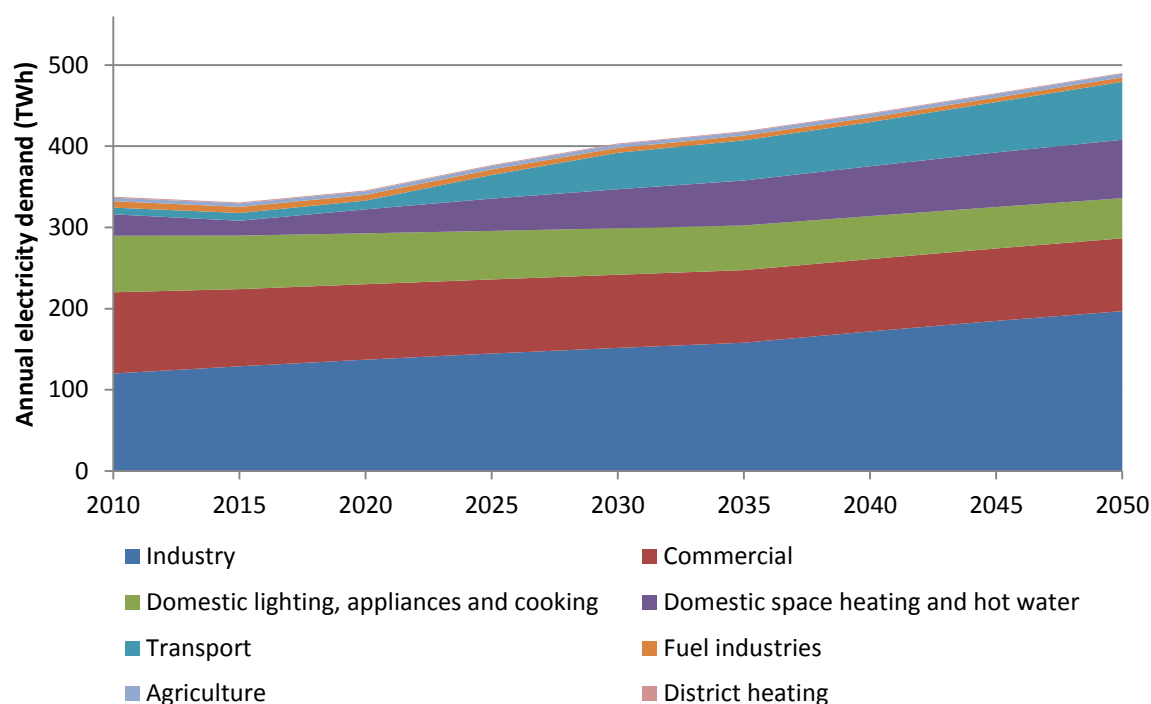


Figure 4.3. Annual electricity demand (TWh) in 'Higher renewables, more energy efficiency' future 2010-2050 (based on HM Government, 2011)

To meet this growth, generating capacity including balancing generation increases by 161% over the same period to reach 210 GW (Figure 4.4). This is the highest electricity generation capacity of all the scenarios.

This growth outstrips that of demand primarily due to the dominance of renewables on the system, which accounts for 52% of capacity including backup in 2050. Of the renewables in this scenario, most of the capacity is in onshore and offshore wind, with 28.4 and 54 GW in 2050, respectively. With their comparatively low load factors of 30% for onshore wind and 45% for offshore wind, an increased capacity is required to meet demand. In addition, due to the intermittent nature of these renewables, the scenario requires a significant proportion of the capacity to be accounted for by generation capacity whose function is grid balancing: 24.4 GW of gas, 20 GW of storage and 30 GW of interconnection.

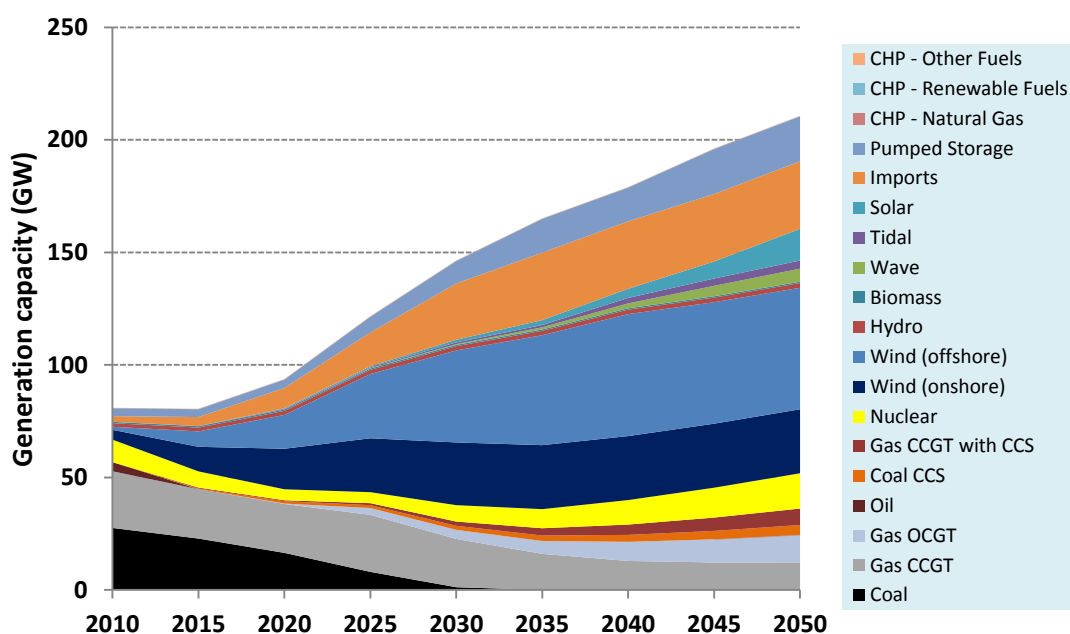


Figure 4.4. Generation capacity (GW) in 'Higher renewables, more energy efficiency' future 2010-2050 (based on HM Government, 2011)

Timeline

To 2020, growth in wind power is almost entirely responsible for offsetting the decline in coal and nuclear power as the current fleet of these generators are retired. To 2030, new nuclear power and commercial CCS plants begin to emerge, but closures continue to hold down the proportion of nuclear on the grid. Over the same period, offshore wind continues to grow strongly, adding 16 GW to the system, compared to 10 GW of onshore wind. Between 2030 and 2050 growth in wind falls to zero, while CCS and nuclear continue to expand. Other renewables, notably, solar PV, wave and tidal, are deployed in higher levels between 2040 and 2050.

4.3. 'Higher nuclear, less energy efficiency' future

Overall trends

This scenario sees a very limited effort to reduce energy demand across the economy through behaviour change or energy efficiency measures. Large-scale electrification of transport and heating drives increases in electricity demand, which increases by 60% (Figure 4.5). Of the four DECC scenarios, the electricity demand in 2050 is the highest at 555 TWh. However, electricity generation capacity growth grows by only 51% to reach 123 GW (Figure 4.6). This growth rate is less than the increase in demand due to the high penetration of nuclear generation in 2050 which has a high capacity factor of 80%. This deployment of nuclear increases the average capacity factor of generation on the grid.

There is small but significant role played by storage, interconnection and gas power in 2050, with 11.3 GW of backup gas capacity, 4 GW of storage and 10 GW of interconnection.

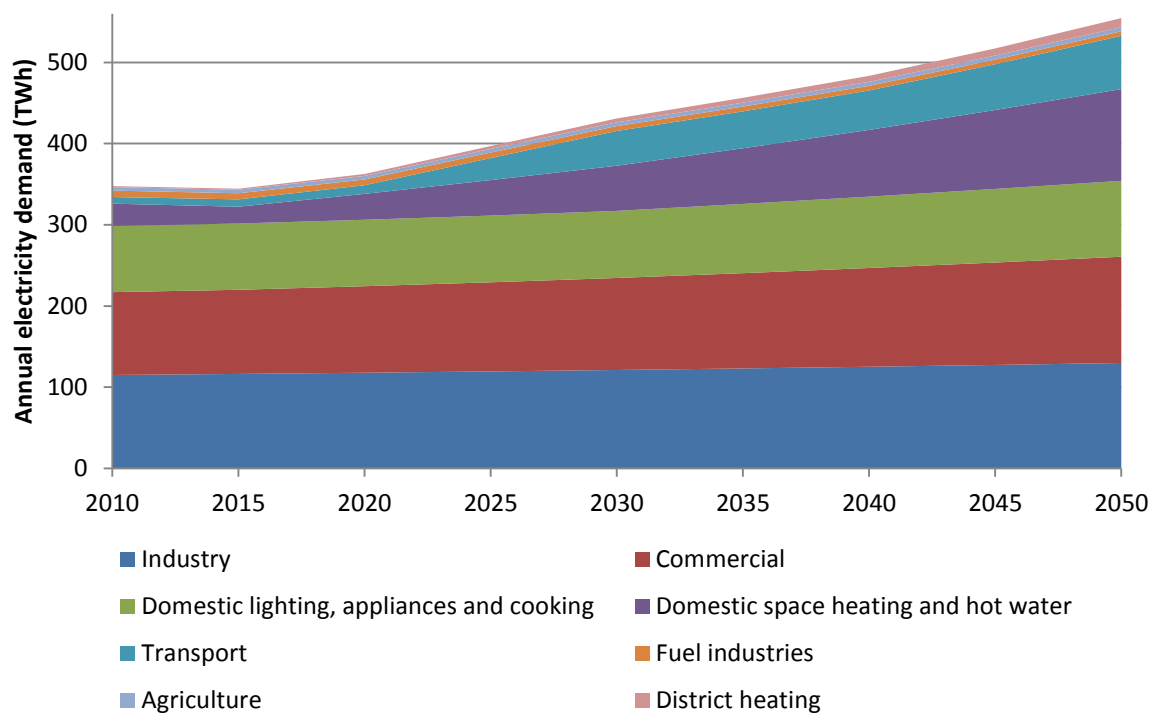


Figure 4.5. Annual electricity demand (TWh) in ‘Higher nuclear, less energy efficiency’ future 2010-2050 (based on HM Government, 2011)

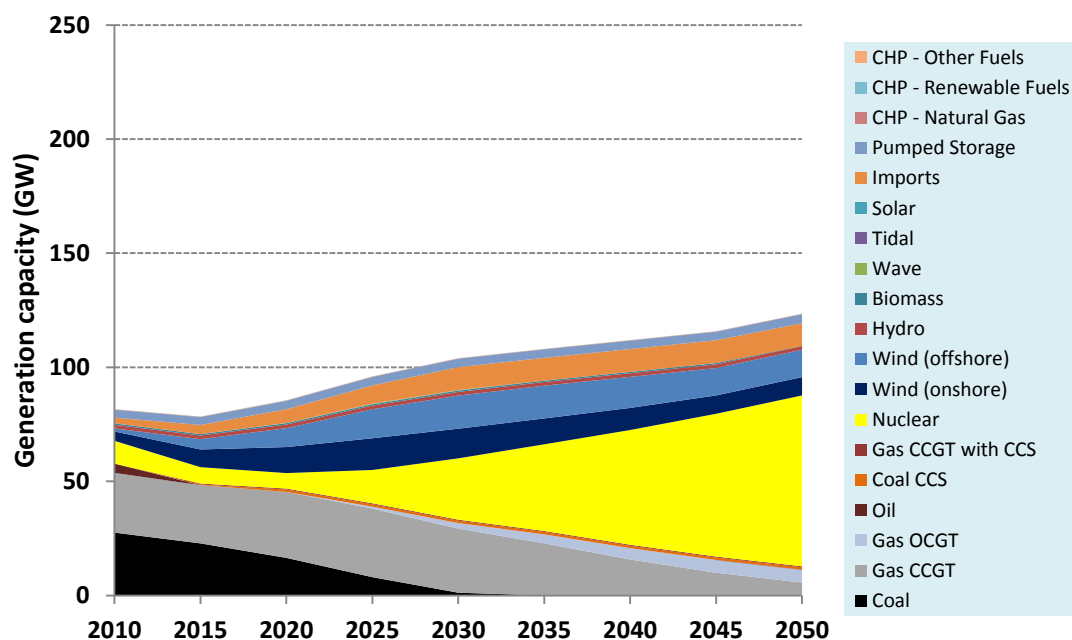


Figure 4.6. Generation capacity (GW) in ‘Higher nuclear, less energy efficiency’ future 2010-2050 (based on HM Government, 2011)

Timeline

Due to the long lead times for nuclear, significant new rollout does not begin until from 2025. Although by 2020, 3.2 GW of new plant is added to the system, the closure of 6.4 GW of legacy plant in the previous 10 years results in a minimum penetration of nuclear power.

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At this stage 1.5 GW of demonstration CCS plant has been built but no commercial deployment takes place.

New nuclear build rates are ramped so that beyond 2025 almost 2.5 GW of new plant is built per year, a rate that is maintained to the end of the scenario, by which time 75 GW of nuclear are installed. However, this delay, along with the closure of coal plants and growing electricity demand requires non-nuclear capacity to fill the gap. Up to 2020 new gas capacity is built, and the cheapest renewable source – wind power – plays an important short-term role. Onshore wind is added at a steady and continuous rate up to 2025 when its deployment peaks, and capacity declines to 2050. Offshore wind follows a similar pattern, peaking shortly after 2025, then gently declining as nuclear capacity expands. By 2050 the generation system is dominated by nuclear power, which accounts for 61% of capacity including backup.

4.4. 'Higher CCS, more bioenergy' future

Overall trends

In this scenario, there is medium level of energy demand and investment in energy efficiency. However, there is only limited electrification of transportation which results in minimal growth in annual electricity demand to 2050 to 461 TWh, a 34% increase on 2010 levels (Figure 4.7). In 2050 this scenario has a relatively diverse generation mix, with 35% of capacity coming from CCS, 29% from renewables, and 19% from nuclear. In this scenario storage, interconnection and gas backup plays a very limited role in grid balancing due to the ability in the DECC 2050 calculator for CCS and nuclear to provide increased output to compensate for intermittent output from renewable generators. The generation capacity in this scenario is the lowest of the four DECC pathways, increasing to 101 GW in 2050.

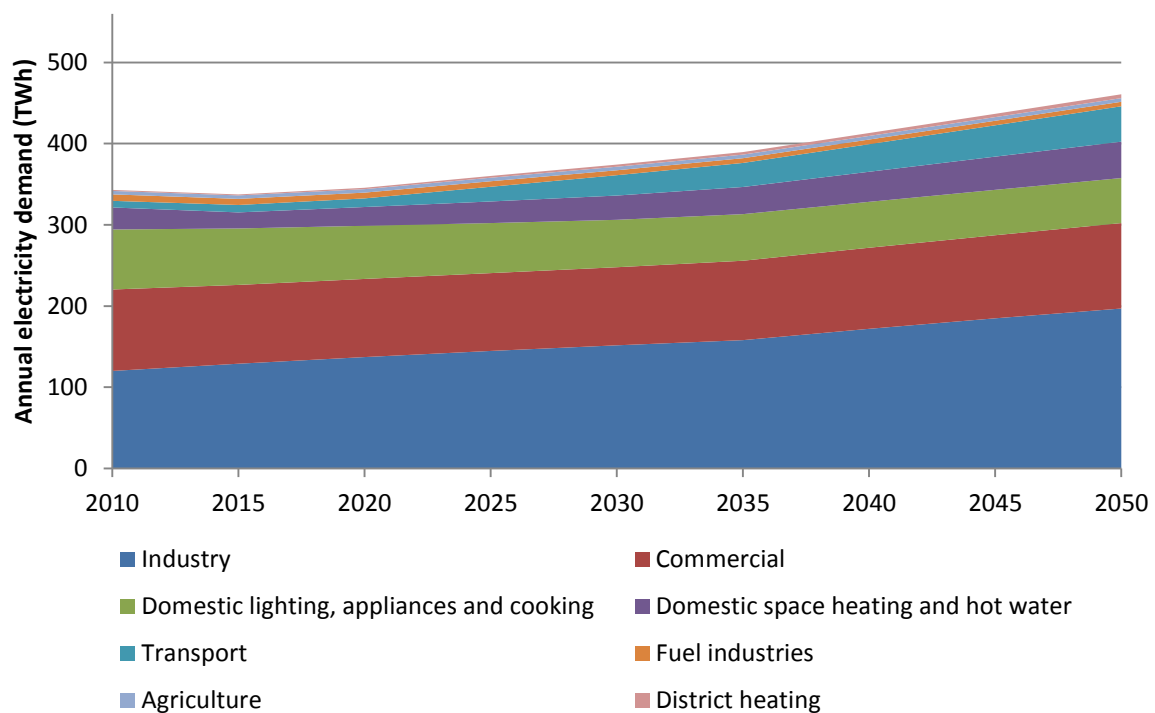


Figure 4.7. Annual electricity demand (TWh) in 'Higher CCS, more bioenergy' future 2010-2050 (based on HM Government, 2011)

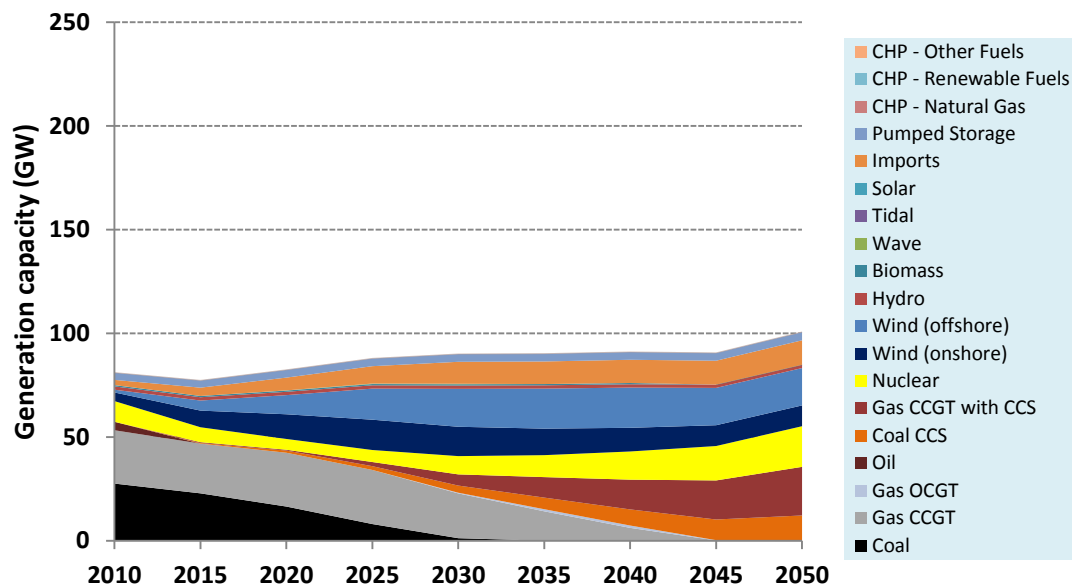


Figure 4.8. Generation capacity (GW) in 'Higher CCS, more bioenergy' future 2010-2050 (based on HM Government, 2011). Note: By 2050, 77% of coal CCS is co-fired biomass, and 15% of gas CCGT with CCS is biogas.

Timeline

As in the other scenarios, electricity demand declines slightly to 2015. Consistent with the reduced electricity demand, generation capacity decreases to 2015, although it subsequently increases through to 2050. The capacity added to 2030 is primarily from the renewables, which offsets the decline of coal as gas stays roughly flat. Over the same period, new nuclear build compensates for legacy plant closures. From 2030 onwards large deployment of CCS commences, with new build rates increasing to around 1.5 GW per year. Over the same time gas declines rapidly to zero in 2045, while nuclear begins to accumulate on the system and the proportion of capacity accounted for by nuclear increases. This leads to a static capacity from 2025 to 2045. Between 2045 and 2050 the expansion of CCS drives generation capacity up to its highest level over the modelled period. It is important to note that the co-firing of biomass with coal CCS and biogas with gas CCS implies the potential for net negative CO₂ emissions in this scenario.

The high capacity factor of CCS – 85% – means that generation capacity of this type can have a large impact on generation. While electricity generation matches electricity demand plus losses for most of the modelled period, the large increases in capacity from 2045 to 2050 result in excess electricity production and net exports of 14.7 TWh.

Summary

The DECC scenarios all show significant increases in capacity of one or more of the key low carbon generation technologies needed to meet increases in electricity demand. The Core MARKAL scenario has the most balanced mix of the three main low carbon technologies, with 31 GW of nuclear, 25 GW of coal, biomass and gas generation with CCS, and 49 GW of

renewable generation by 2050. This mix, together with increases in average capacity factors, means a relatively modest increase in overall capacity to 112 GW by 2050. As this scenario is produced using the MARKAL model to optimise the pathway to meeting the carbon budgets and the 80% reduction target by 2050, this assumes that investment decisions are made in a cost optimal way. Whilst this provides a useful benchmark for comparison with other pathways, it must be remembered that technological and institutional path dependencies and bounded rationality of firms and individuals mean that optimal decisions are unlikely to always be made.

Hence, the three other scenarios were designed using the 2050 Calculator to examine options in which investment is focussed more on one of the three technology areas. In the *'higher renewables, high energy efficiency'* scenario, electricity demand rises, despite improvements in energy efficiency for homes and industry, due to increases in the use of electricity for transport, home heating and industry. This requires more than doubling of electricity capacity to 210 GW by 2050, with the largest share coming from 54 GW of offshore wind, and high levels of back-up gas generation, storage and interconnection. In the *'higher nuclear, less energy efficiency'* scenario, higher levels of electricity demand are met with a comparatively lower installed capacity of 123 GW (including storage and interconnectors). However, this requires 75 GW of nuclear power to be installed by 2050, which is assumed to operate at a capacity factor of 80%. In the *'higher CCS, more bioenergy'* scenario, there is less focus on electrification of home heating and again high capacity factors are assumed for nuclear and thermal generation with CCS. This leads to a more modest generating capacity of 100 GW in 2050, including 35 GW with CCS. The 80% reduction target in 2050 is met thanks to 'negative emissions' resulting from power generation of biomass and biogas in thermal plants with CCS.

The following sections compare in more detail the characteristics and assumptions of the transition pathways and DECC scenarios, in order to understand better what would be needed to realise any of these pathways.

5. Scenario comparisons

This section begins by comparing the assumptions on capacity factors between the pathways and scenarios since these make significant differences to the levels of installed capacity needed. It goes on to compare the annual electricity demand, capacity and output across the scenarios in 2050, before examining the implications for particular technologies in the next section.

5.1. Capacity factors

The assumed capacity factors for each of the generation scenarios are important because they affect the amount (GW) of capacity that is necessary for general grid operation, and influence the amount of demand-side management and backup requirements of the grid. A comparison of the maximum capacity factors for the DECC scenarios and Transition Pathways is shown in Table 5.1.

	DECC scenarios ⁵	Transition Pathways
Coal	60%	48%
Gas	70%	56%
Oil	6%	13%
CCS	85%	90%
Nuclear	80%	61%
Onshore wind	30%	29%
Offshore wind	45%	43%
Hydro	38%	37%
Biomass	90%	61%
Wave	23%	28%
Tidal range	20-24%	24%
Tidal stream	40%	24%
Solar	10%	11%

Table 5.1: Maximum capacity factors in 2050 for different models. Transition pathways capacity factors are maximum values across the three pathways

In the DECC calculator, capacity factors are fixed for any particular year for all technologies except biomass/coal. Most are also invariant over the modelled period, except nuclear, which increases from 60 per cent in 2010 by 2 per cent per year to reach 80 per cent in 2020, and offshore wind, which gradually increases from 35 per cent in 2015 to 45 per cent

⁵ These compare to capacity factors in 2010 for nuclear of 60% and offshore wind of 35%. Source: DECC, 2012b
Realising Transition Pathways

in 2035. In contrast, in the Transition pathways study, capacity factors for the non-thermal generators – wind, hydro, wave, tidal and solar – are static from 2010 to 2050, but for thermal generation vary from year to year. Conventional fossil fuel thermal generation – coal, gas and oil – trend downwards to zero; coal generation is gone from the system by 2035, and oil at the latest by 2020.

The most significant difference in these figures is for nuclear power. In 2010, values from both DECC and the Transitions pathways study are in line with current values (Figure 5.1). However, in the DECC calculator, nuclear capacity factor increases to levels that have previously been achieved in the UK, but not maintained for extended periods. It is unclear how much capacity factors would increase for new build power stations, as the model favoured by EDF – the European Pressurized Reactor (EPR) – is not yet operational at any of the sites at which new build are being constructed. However, Areva (2005) claims an availability factor of “up to 92%, on average, during the entire service life of the plant”.

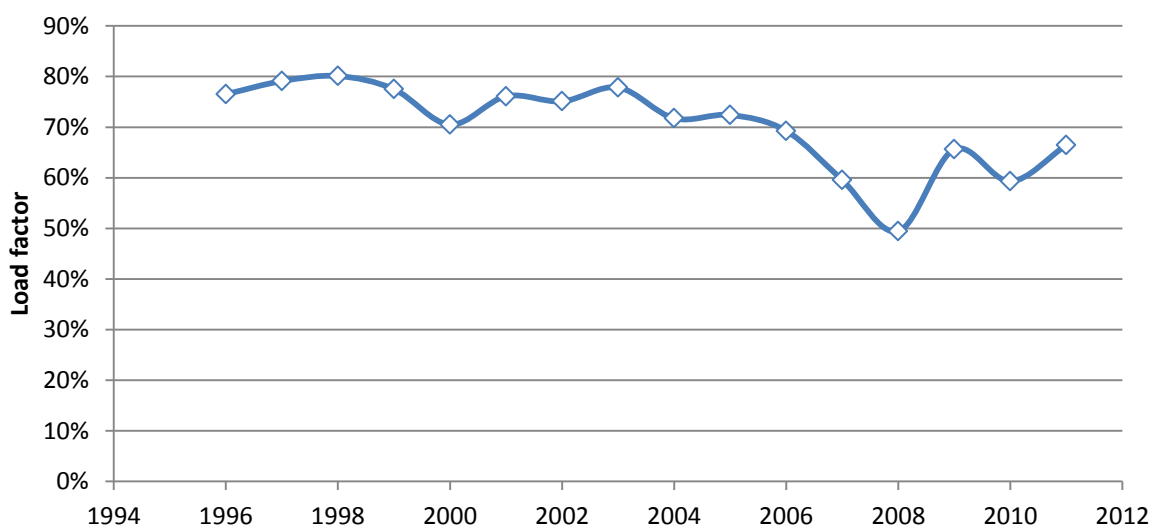


Figure 5.1: Load factor for nuclear power from 1996 to 2011. Source: DECC, 2012b

How the capacity factor of gas should be viewed is not straightforward. A proportion of gas generation is, in most cases, needed to balance the grid in the case of a supply shock. Such a supply shock can occur when there is high electricity demand (e.g. in times of low external temperatures) and low output from renewables on the grid. The impact of this, and consequently the requirement for backup, clearly depends to some extent on penetration of renewables on the grid.

However, in the DECC calculator, back-up generation makes no contribution to annual electricity generation figures. As a result, the capacity factors for gas in the DECC scenarios and the transition pathways, based on the calculated generation data, reduce to close to zero by 2050. When the need for backup generation is included in capacity factor calculations, the capacity factors for gas power stations in the DECC scenarios move closer to those in the Transition Pathways study (Figure 5.2), but there are still considerable differences between the DECC scenarios and those of the Transitions Pathways study. This is

while the gas generation capacities in the models are broadly similar, at least until 2030 (see Table 5.2).

Pathway	2030	2050
Renewables	25.5	24.0
Nuclear	30.5	11.0
CCS	21.9	0.0
Market rules	26.7	0.0
Central coordination	20.7	5.4
Thousand flowers	20.7	15.0

Table 5.2: Gas capacity (GW) in 2030 for different scenarios

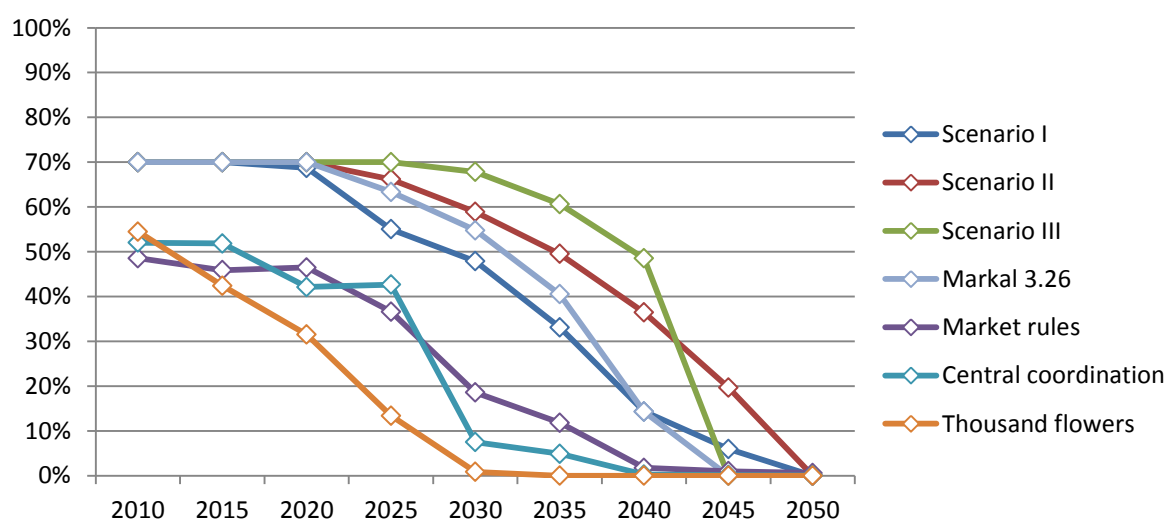


Figure 5.2: Load factor for gas generation including backup generation in DECC scenarios

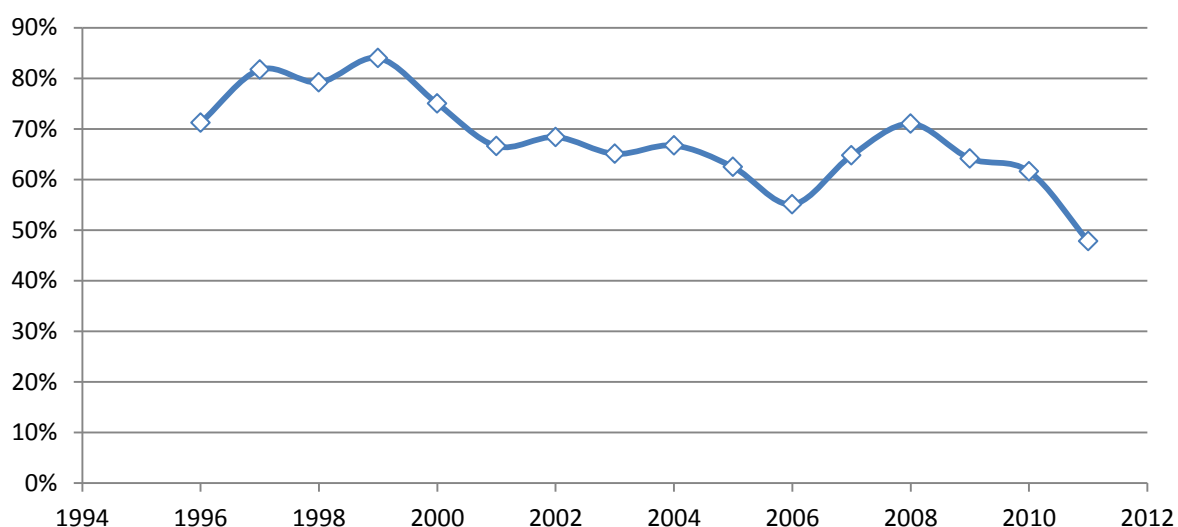


Figure 5.3: Load factor for gas CCGTs from 1996 to 2011 Source: DECC, 2012b

5.2. Scenario differences

The demand for electricity in 2050 for all seven scenarios is compared in Figure 5.4. The *Thousand Flowers* scenario is the only one in which electricity demand decreases from 2010 to 2050. The one in which demand is the largest is the second of DECC's scenarios, which focuses on nuclear power and does not prioritise energy efficiency. The results from these scenarios suggest that in the absence of a motivated civil society which takes responsibility for climate change mitigation, electricity demand reductions are not likely, even with very high levels of energy efficiency as seen in DECC's higher renewables, higher energy efficiency pathway. However, this is not inconsistent with 80 per cent greenhouse gas emissions reductions by 2050.

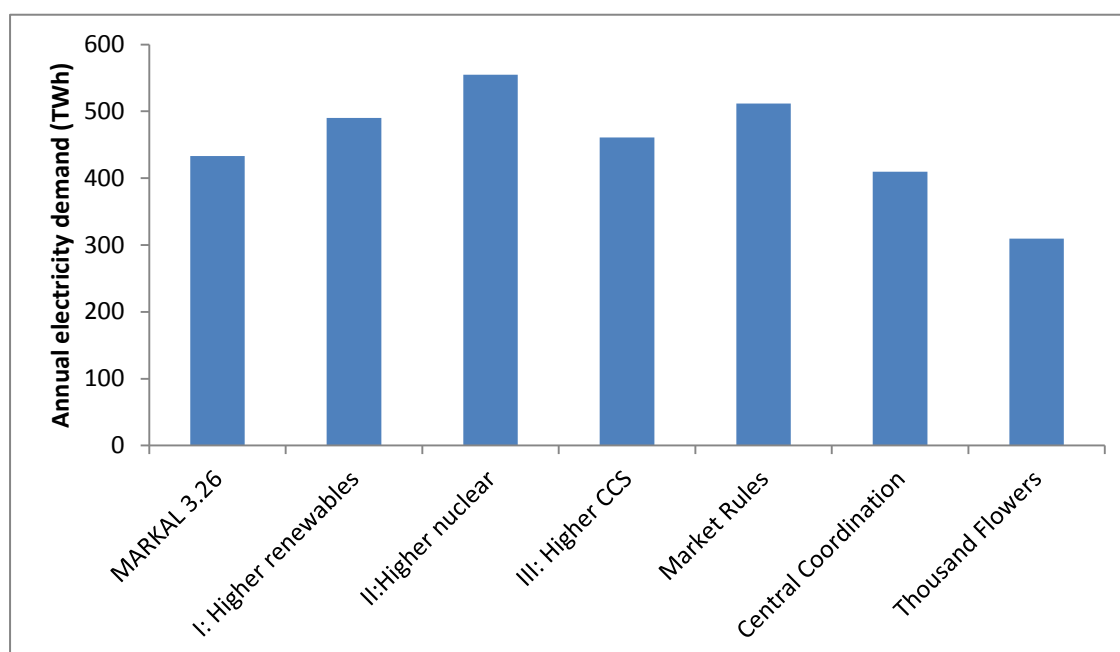


Figure 5.4: Electricity demand (TWh) in 2050 under DECC scenarios (left) and three Transition Pathways scenarios (right)

The generation capacity for the different scenarios, including back-up gas capacity, storage and interconnection in the DECC scenarios, is shown in Figure 5.5. Although all except the *Thousand Flowers* scenario rely heavily on CCS, nuclear and wind, there is a diverse range of generation mixes. Due to the lower capacity factors of renewables, those with a large amount of this type of generation tend to have a higher generating capacity. All of the scenarios except the higher CCS scenario show a large increase in generation capacity by 2050 on today's level of around 90 GW.

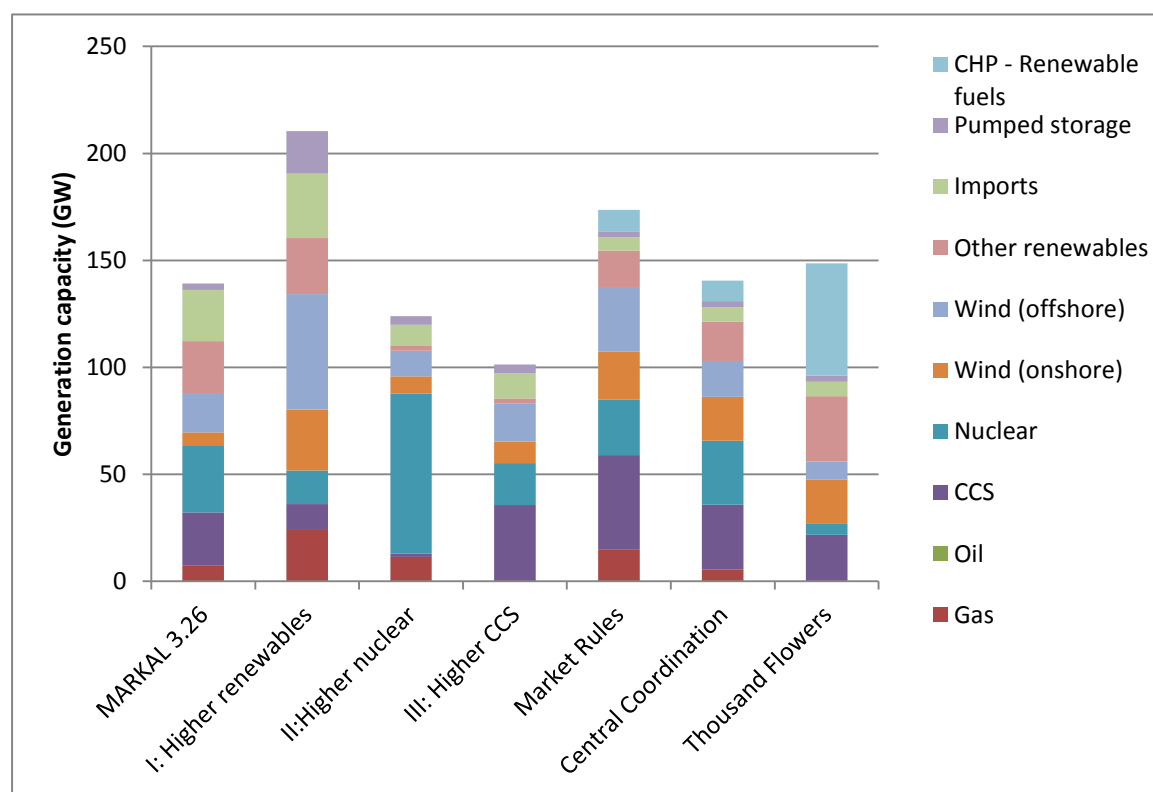


Figure 5.5: Generation capacity (GW) for DECC scenarios and transition pathways in 2050, including peaking gas, interconnection and pumped storage in DECC scenarios

The annual UK electricity generation in 2010 and 2050 for the MARKAL scenario and Transition Pathways is shown in Figure 5.6. This shows that the total electricity generation in 2050 for the *Market Rules* pathway is similar to that for the MARKAL scenario, though with a higher proportion of renewables. The total generation is lower in the *Central Co-ordination* pathway, and significantly lower in the *Thousand Flowers* pathway (to below the output in 2010, despite the expansion of electric vehicles in this pathway).

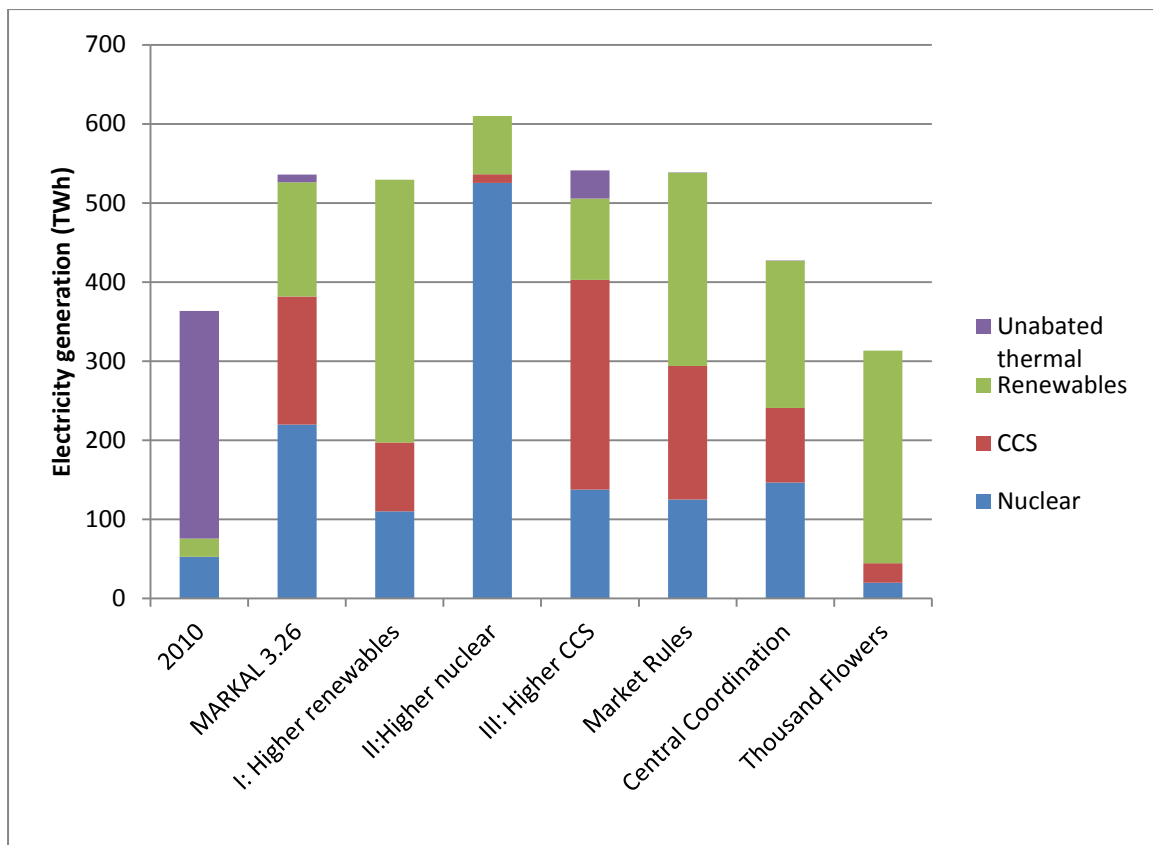


Figure 5.6. Annual UK electricity generation (TWh) in 2010 and 2050 under DECC scenarios and Transition Pathways

6. Technology implications

The above comparisons show that all these scenarios and pathways imply high levels of deployment of some or all low carbon generation technologies, as well as ranges of energy efficiency improvements. This section considers in more detail the implied deployment rates for some key technologies.

This is done in reference to the deployment trajectory levels within the DECC 2050 calculator, which range from level 1- little or no effort made, to level 4- extremely ambitious targets that push towards the technical or physical limits of what can be achieved (HM Government 2010a).

6.1. Nuclear

The core MARKAL and '*higher nuclear, less energy efficiency*' scenarios, as well as the *Market Rules* and *Central Co-ordination* pathways, all imply a significant expansion of the UK's nuclear capacity from the current value of 11 GW from 2030 onwards. The '*higher renewables, more energy efficiency*' and '*higher CCS, more bioenergy*' scenarios show a smaller increase in nuclear capacity. Only in the *Thousand Flowers* pathway, does nuclear play no significant role (in line with DECC trajectory level 1).

Rising nuclear generation capacity reflects the UK government's belief that nuclear power has a role to play in the future UK energy mix alongside low carbon technologies and that energy companies should be given the option to invest in new nuclear build (DECC, 2011). The minimum (level 1) trajectory implies that there is a change in government thinking and that nuclear is no longer seen as a favoured technology. The core MARKAL scenario assumes a deployment rate corresponding to level 1.7 in the DECC 2050 calculator, which implies that 2.5 GW of nuclear capacity is in place by 2020, with just under 1 GW of capacity added annually thereafter, leading to 31 GW installed capacity by 2050. This is equivalent to 2 new nuclear power stations of capacity 1.5 GW coming on line every 3 years from 2020 to 2050. The DECC '*high nuclear, less energy efficiency*' scenario assumes a trajectory level of 2.7 resulting in a 2.5 GW/year build rate from 2025, equivalent to 3 new power stations every 2 years, leading to a 75 GW installed capacity by 2050. The *Market Rules* pathway implies a similar trajectory to the core MARKAL scenario, leading to 25 GW of capacity by 2050, and the *Central Co-ordination* pathway implies a similar end-point of 30 GW capacity by 2050, though with a more rapid build-up in earlier years of this pathway to reach 22 GW of installed capacity by 2030. The installed capacity and annual build rates for all the scenarios are shown in Figures 6.1 and 6.2.

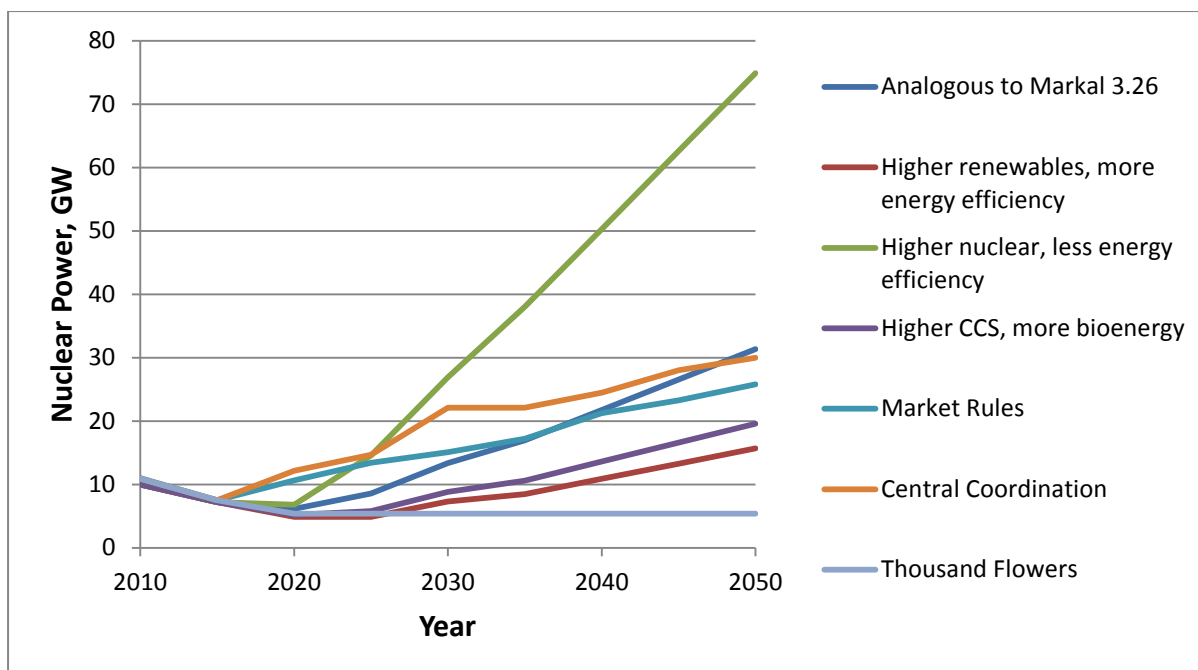


Figure 6.1. Installed capacity (GW) for nuclear power to 2050 in the MARKAL, DECC and Transition Pathways

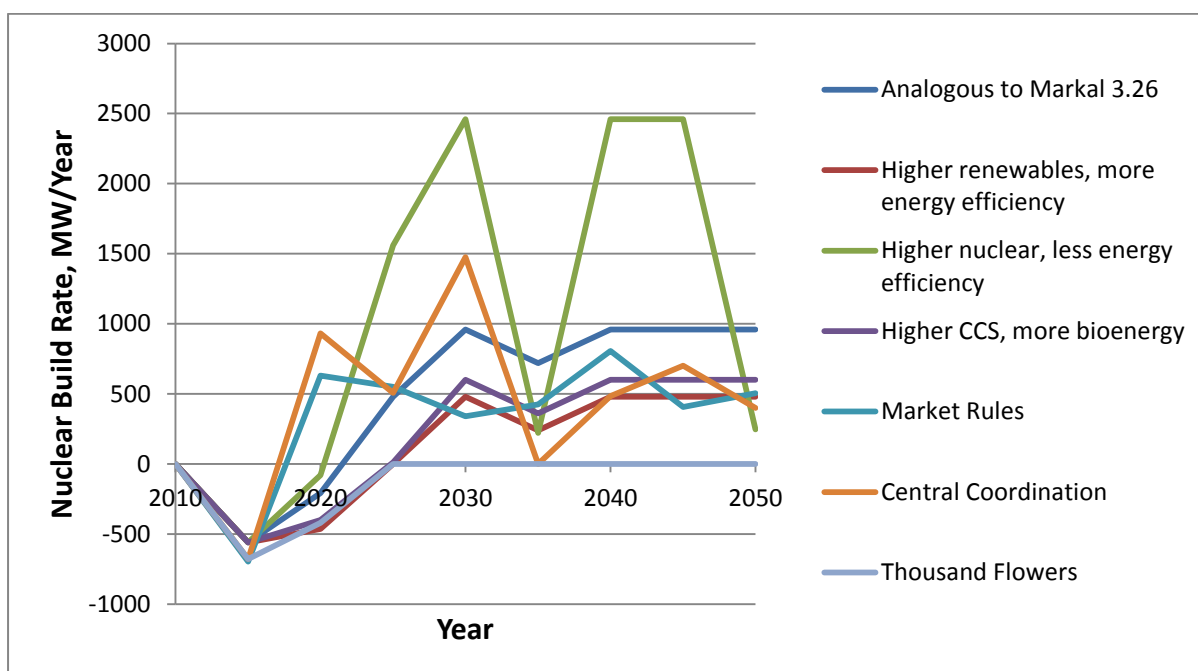


Figure 6.2. Annual build rates (MW/year) for nuclear power to 2050 in the MARKAL, DECC and Transition Pathways (net of closures to 2030)

In order to meet the deployment levels seen in the pathways there would need to be clear support by both the public and government, with regulatory certainty regarding the acceptability of reactor design and market certainty giving operators confidence that they will see a return over the lifetime of the project. In order to incentivise deployment, the UK government has identified eight possible sites for new nuclear power stations, with one reactor at each site this could result in the addition of 10-14 GW capacity by 2025 (DECC,

2011). It has provided support through the Contract for Difference feed-in tariff under the Electricity Market Reform (DECC, 2012), as well as streamlining the design regulation and planning requirements. However, the high capital costs of new nuclear power stations, as well as continuing concerns amongst sections of the public over safety, waste management and nuclear proliferation, remain significant barriers to a large scale-up of nuclear power in the UK.

6.2. Carbon capture and storage

Carbon capture and storage (CCS), or carbon sequestration, also plays a significant role in most of the scenarios and accounts for a similar percentage of the total generation in all the scenarios except the *Thousand Flowers* and the DECC '*High nuclear*' pathways. The core MARKAL scenario assumes a build rate corresponding to trajectory level 1.6, which implies that 1.7 GW of demonstration capacity is in place by 2020, with 5 GW of commercial capacity by 2030 and just under 1 GW added annually, leading to 25 GW of capacity with CCS by 2050. In the '*high CCS, more bioenergy*' scenario, this increases to 1.5 GW per year added from 2030, leading to an installed capacity of 40 GW by 2050. In contrast, in the '*high nuclear, less energy efficiency*' scenario, no further CCS capacity is built after the initial 1.7 GW demonstration capacity. The *Market Rules* pathway is similar to the 'high CCS' scenario, with 44 GW of capacity with CCS by 2050, though with 21 GW of capacity already by 2030. The *Central Co-ordination* pathway is similar to the core MARKAL scenario, with 30 GW of capacity with CCS by 2050, though with 18 GW of capacity already by 2030. The *Thousand Flowers* pathway also has 16 GW of capacity with CCS by 2030, though this rises to only 21 GW by 2050, as more distributed generation is favoured. The installed capacity and annual build rates for all the scenarios are shown in Figures 6.3 and 6.4.

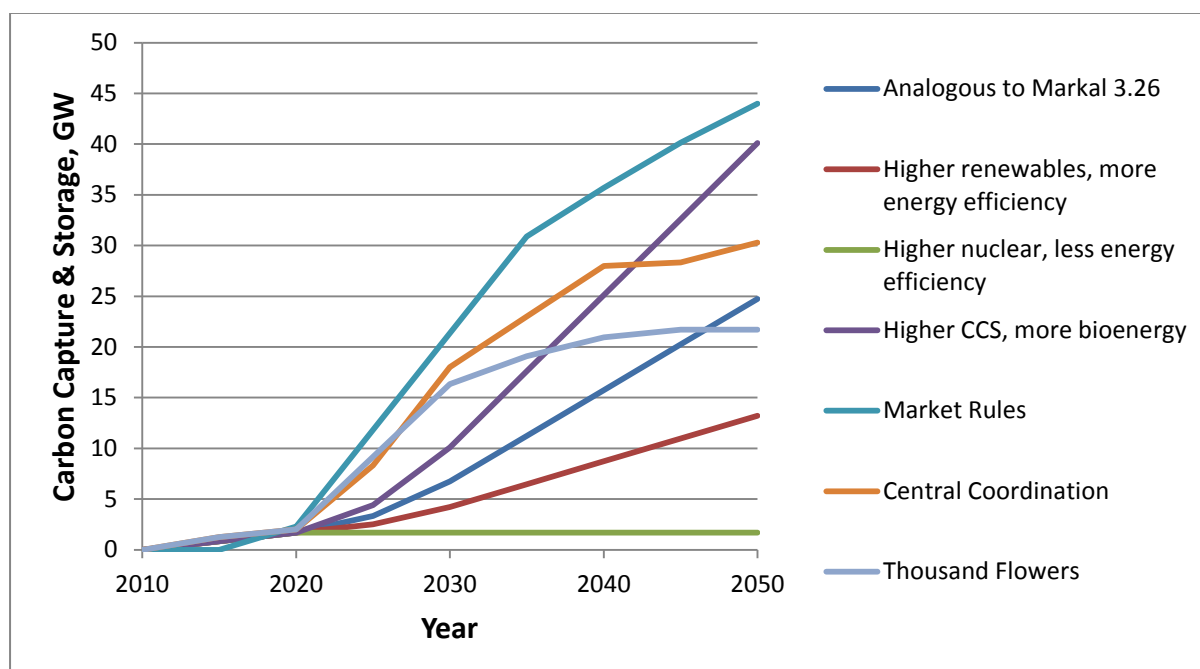


Figure 6.3. Installed capacity (GW) for carbon capture and storage (for coal and gas) to 2050 in the MARKAL, DECC and Transition Pathways

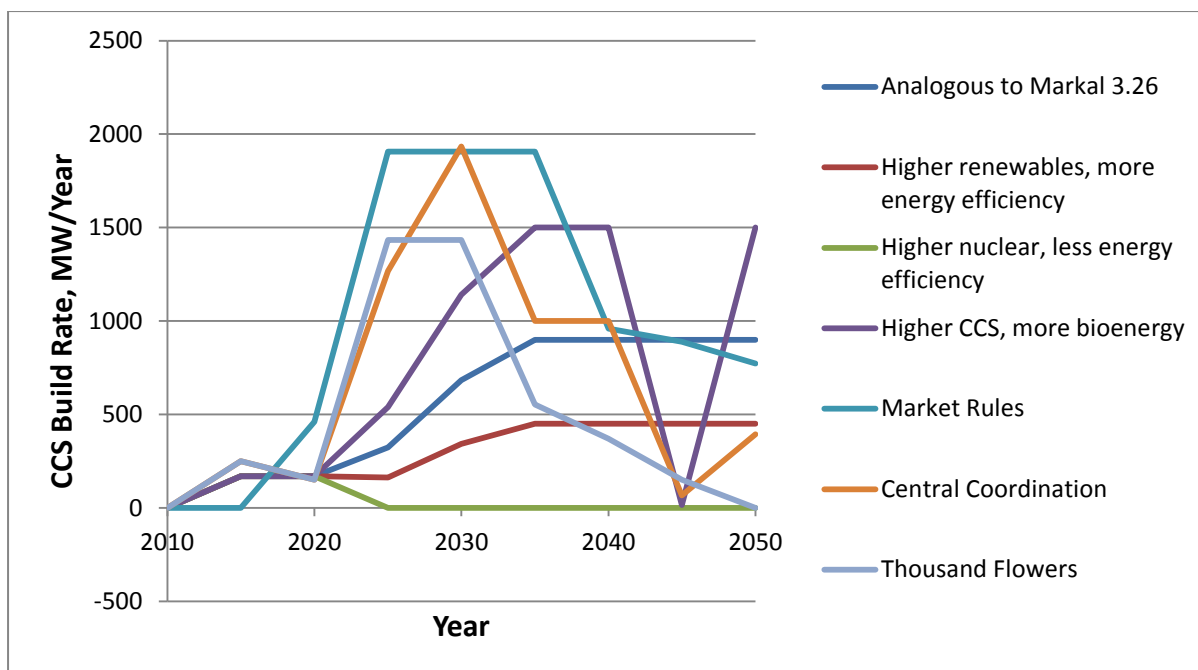


Figure 6.4. Annual build rates (MW/year) for carbon capture and storage (for coal and gas) to 2050 in the MARKAL, DECC and Transition Pathways

There is an energy penalty associated with CO₂ capture that reduces the overall efficiency of the power plant. In the DECC calculator, this is assumed to range initially from 13 to 27%, depending on the type of power plant, gas, pre-combustion solid or post-combustion solid. This energy penalty is assumed to reduce, as the efficiency of the capture process improves, to 12 to 16% from 2020 (cf Gough et al., 2012). Attention must also be given to the reduction of carbon emissions by installing CCS technology. The DECC calculator assumes that 90% of CO₂ emissions are captured, but research by the Transition Pathways team shows that, when life cycle effects are taken into account, this can reduce to a 70% capture rate over the life cycle (Hammond et al., 2013).

The UK government is currently working with industry to support the development of a cost-competitive CCS industry in the 2020s, through a £1 billion commercialisation competition, support for R&D and innovation, and the electricity market reform programme, though only a small number of small-scale CO₂ capture demonstrations have so far been implemented (DECC, 2011).

6.3. Onshore wind

In the core MARKAL scenario, 0.7 GW of onshore wind are added annually from 2010 to 2025, with 0.3 GW added annually thereafter. However, as turbines are only projected to have lifetimes of 20 years, this is below the replacement rate, and so the installed capacity peaks at 13 GW in 2025, reducing to 6 GW by 2050. As shown in Table 4.1, this corresponds to a maximum of over 4,700 turbines of size 2.5 MW, reducing to around 2,400 turbines by 2050. Similar rates are seen in the 'high nuclear' and 'high CCS' scenarios, but in the 'Higher renewables' scenario, the installation rate rises to 1.4 GW per year, leading total installed onshore wind capacity to rise to 28 GW by 2030 and to be retained at that level to 2050. A similar final level of deployment of 21 to 23 GW by 2050 is seen in all three transition

pathways, though the deployment is more evenly timed, with only 14 to 15 GW of installed capacity by 2030.

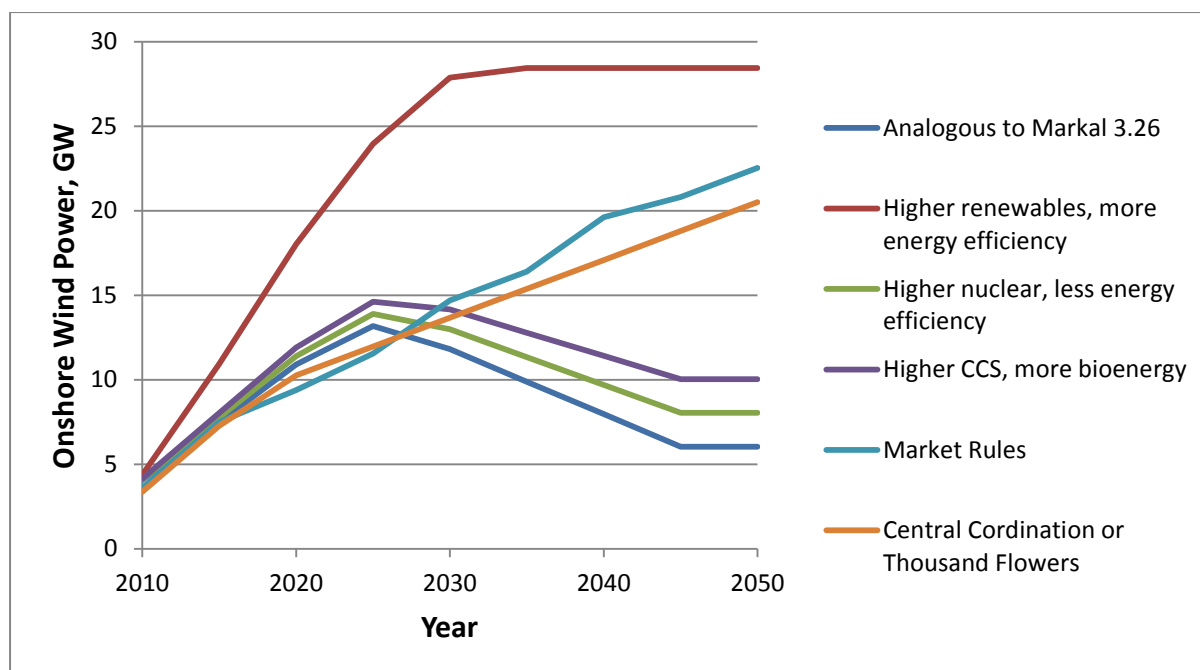


Figure 6.5. Installed capacity (GW) for onshore wind to 2050 in the MARKAL, DECC and Transition Pathways

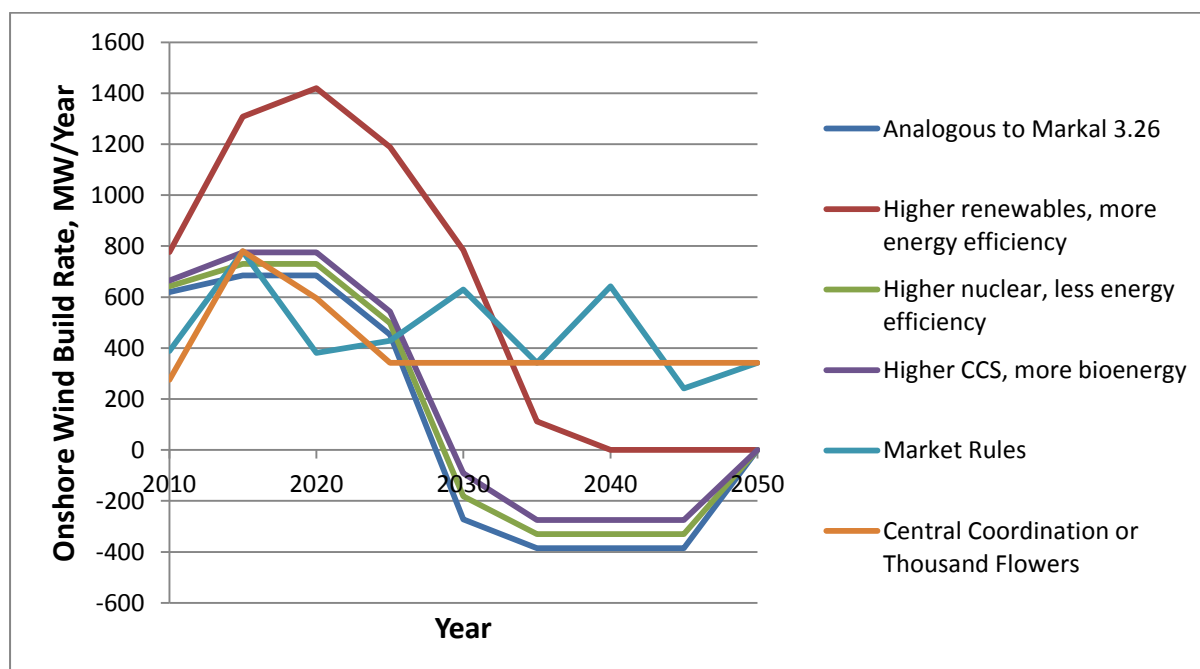


Figure 6.6. Annual build rates (MW/year) for onshore wind to 2050 in the MARKAL, DECC and Transition Pathways (net of closures)

It is assumed that onshore wind will be present in the form of both large scale wind farms and smaller scale community wind projects (HM Government 2010a). The key support

mechanisms for reaching the high deployment levels are the Renewables Obligation (to 2017) and the Contract for Difference Feed-in Tariffs, which will be implemented from 2014 (DECC, 2012), though obtaining planning permission remains an issue.

6.4. Offshore wind

In the core MARKAL scenario, rates of installation of offshore wind increase from 0.7 GW per year to 1.2 GW per year by 2025, thereafter levelling off at 0.9 GW added per year, equalling the replacement rate. This means that offshore wind capacity increases to 18 GW by 2030, before remaining approximately constant to 2050. As shown in Table 1, this corresponds to a maximum of over 3,100 turbines of size 5.8 MW. Similar rates are seen in the ‘high nuclear’ and ‘high CCS’ scenarios, but in the ‘Higher renewables’ scenario, the installation rate rises to 2.7 GW per year from 2025, leading total installed offshore wind capacity to rise to 54 GW by 2040 and to be retained at that level to 2050. The *Market Rules* pathway has rates between these two scenarios, with 30 GW of capacity installed by 2050, though again with a more even ramp up, reaching 15 GW by 2030. Lower rates of installation are seen in the other two transition pathways, only reaching 17 GW of offshore wind by 2050 in the *Central Co-ordination* pathway and 8 GW of offshore wind by 2050 in the *Thousand Flowers* pathway.

Turbine technology has developed since the early stages of deployment with the turbine size increasing from 2 MW seen in UK phase 1 offshore deployment to 3.6 MW in the most recent installations. The deployed turbine size is expected to continue to increase with the Beatrice demonstration project installing two 5 MW turbines and 5-7 MW turbines have been seen in other countries demonstration sites. A 10 MW turbine is also being developed ready for deployment in the North East of England (HM Government 2010a). The pathways assume that 5.8 MW turbines are available.

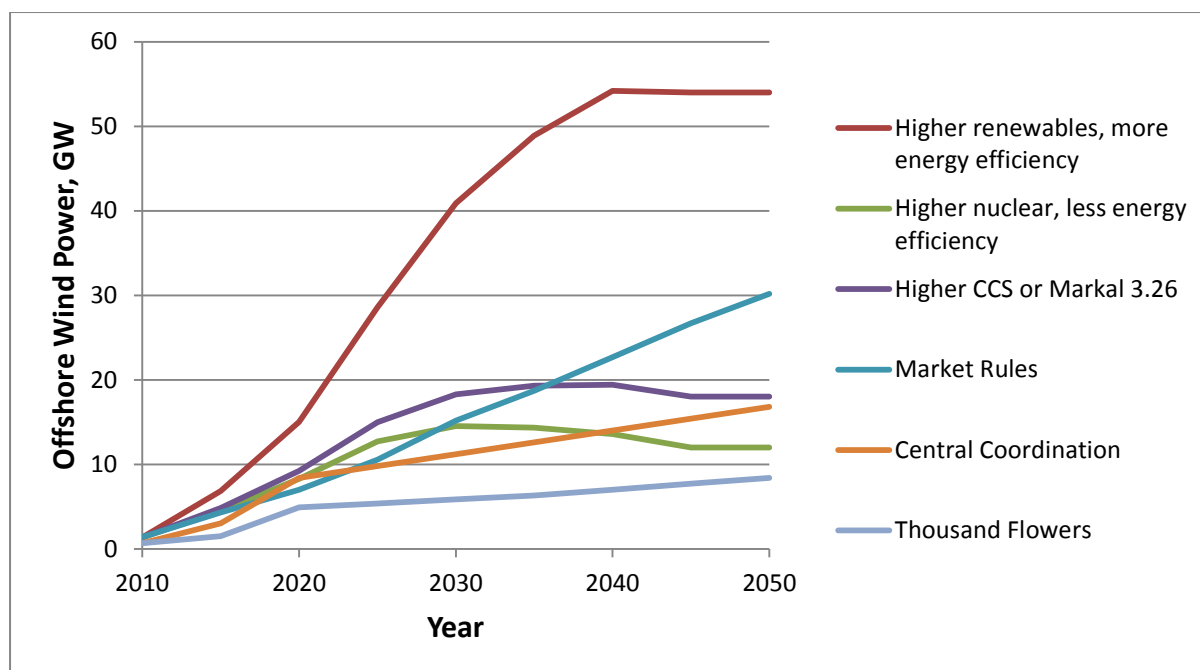


Figure 6.7. Installed capacity (GW) for onshore wind to 2050 in the MARKAL, DECC and Transition Pathways

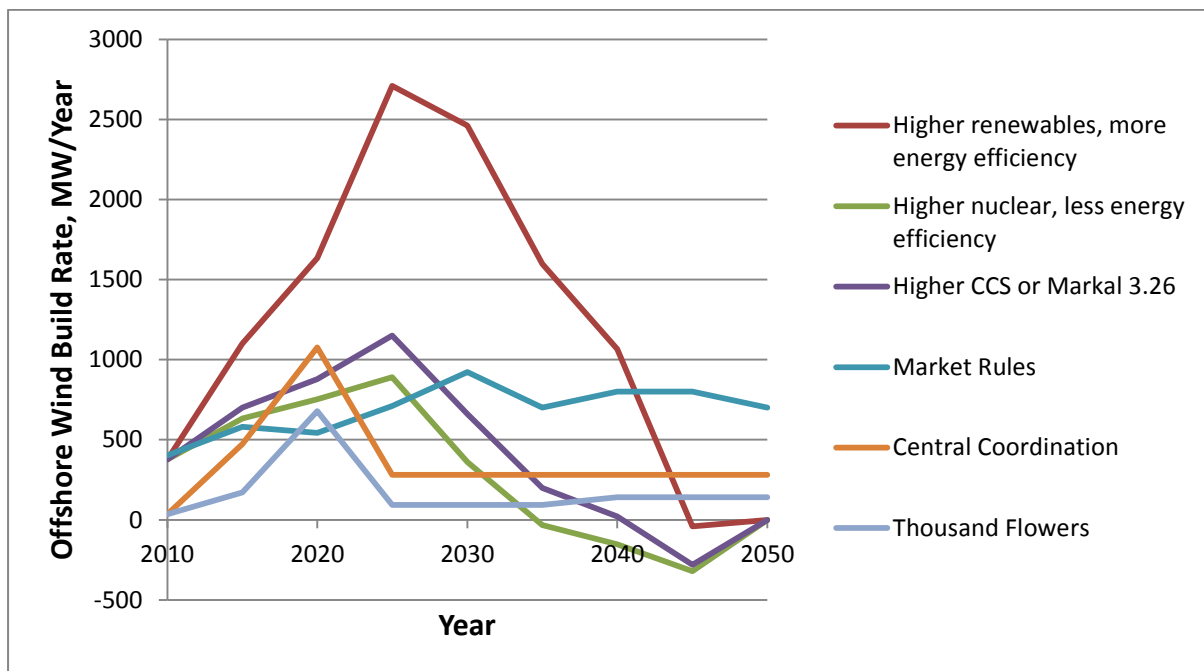


Figure 6.8. Annual build rates (MW/year) for onshore wind to 2050 in the MARKAL, DECC and Transition Pathways

In order to reach the high level deployment of offshore wind the government is supporting technology innovation and demonstration, supply chain development, access to finance through the Green Investment Bank (DECC, 2011), planning and consenting, grid connection, and incentives for investment under the Renewables Obligation (to 2017) and 'contract for difference' feed-in tariffs under Electricity Market Reform, expected to be implemented from 2014 (DECC, 2012).

6.5. Tidal range and tidal stream

Tidal range has the potential to meet 13% of our electricity demand if fully exploited (DECC 2011) and is present in all but the DECC nuclear and CCS pathways. The highest deployment is seen in the core MARKAL and *Market Rules* pathways with around 7.5 GW of tidal range and 5.7 GW of tidal stream installed capacity in 2050. The tidal range capacity equates around 31 sites comparable to the 240 MW la Rance site in France, the only significant tidal range site in operation (DECC 2011). The use of technology that utilises the tidal range is well established and typically has an estimated lifetime of 120 years, the capital costs would be recouped (DECC 2011).

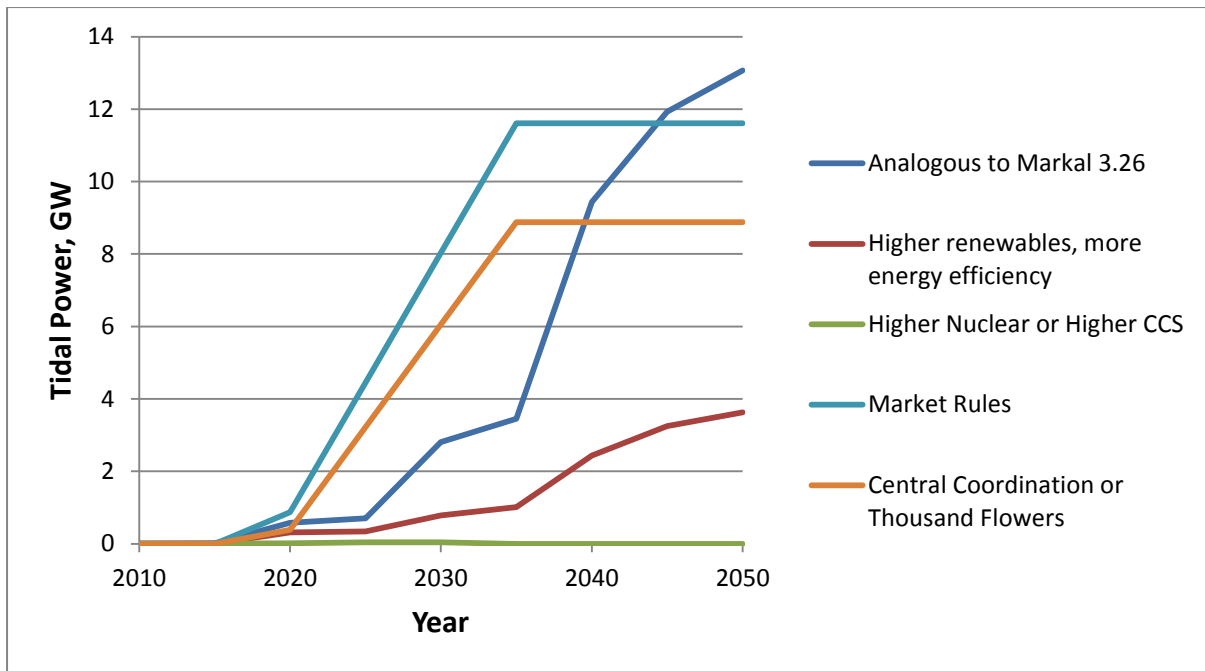


Figure 6.9. Installed capacity (GW) for tidal power to 2050 in the MARKAL, DECC and Transition Pathways

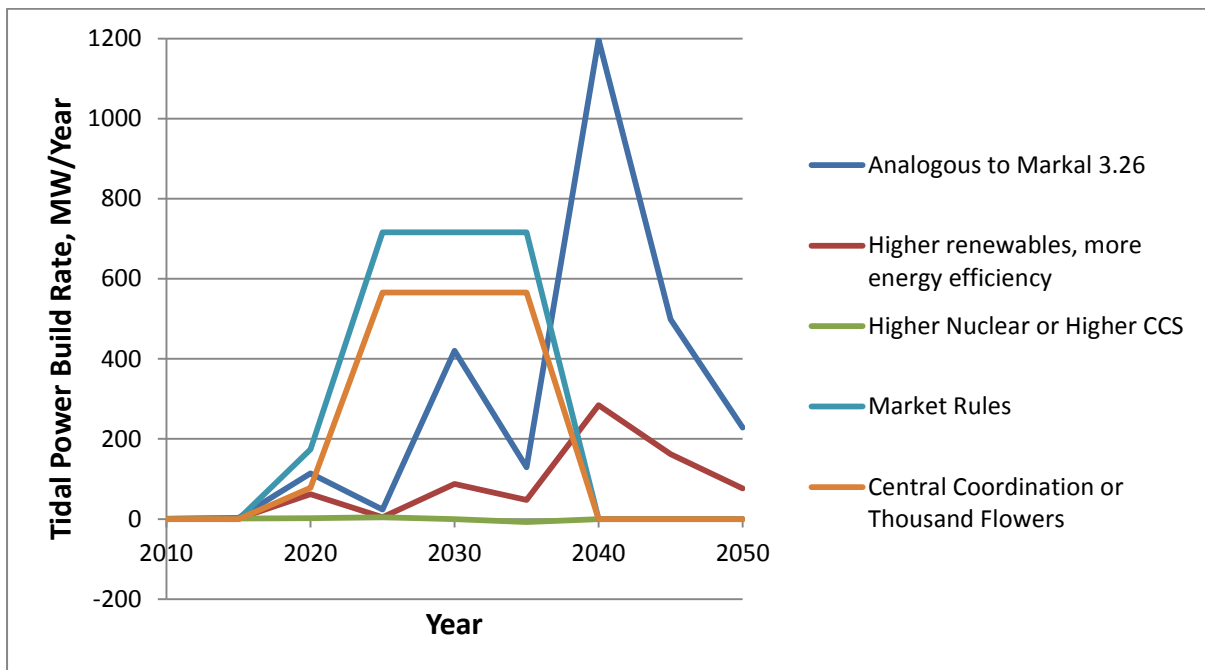


Figure 6.10. Annual build rates (MW/year) for tidal power to 2050 in the MARKAL, DECC and Transition Pathways

The Severn Estuary is seen as one of the premium locations in the world for tidal range but due to the cost, as well as the local environmental impacts, it was decided that Severn tidal barrage would not be required to meet the 2020 renewable energy targets, however the project may still be considered in the future (HM Government 2010b).

6.6. Wave power

These are emerging technologies with the UK at the forefront of research and development through the National Renewable Energy Centre, the European Marine Energy Centre and the WaveHub demonstration facility (HM Government 2010a). The core MARKAL pathway sees the highest deployment with 9.6 GW of wave energy from over 6,400 turbines and 5.7 GW of tidal stream energy from 2,850 turbines in 2050. To achieve commercial deployment of wave and tidal stream, pre-commercial demonstration sites are planned to be deployed between 2013 and 2015, with commercial deployment following (DECC 2011).

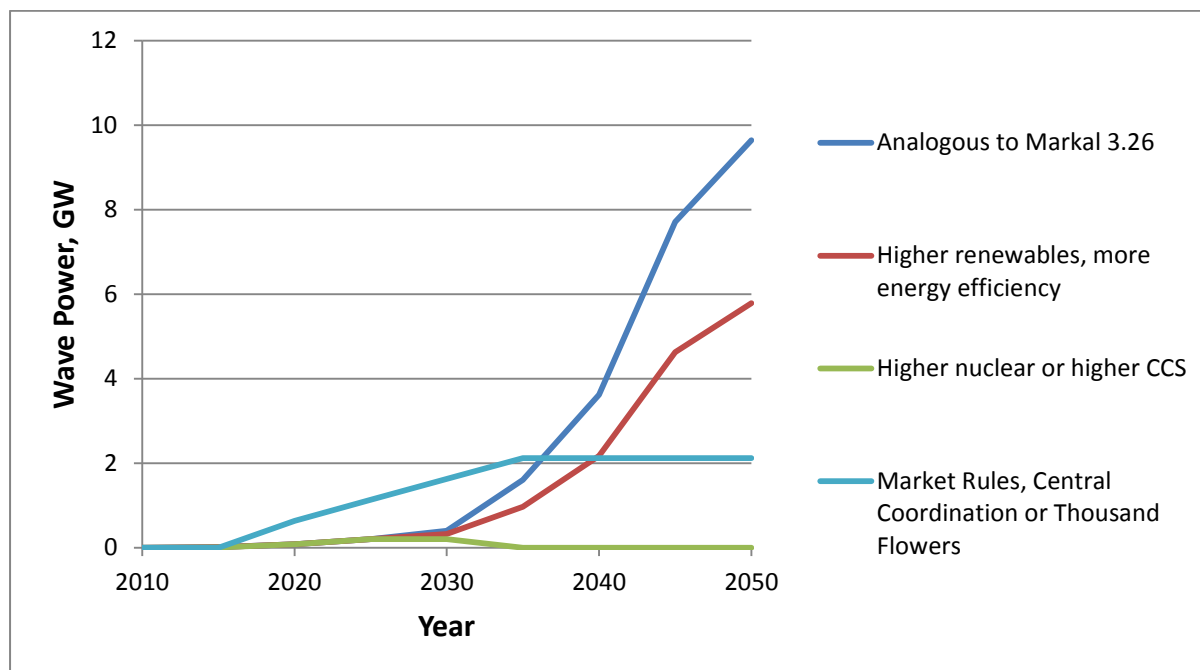


Figure 6.11. Installed capacity (GW) for wave power to 2050 in the MARKAL, DECC and Transition Pathways

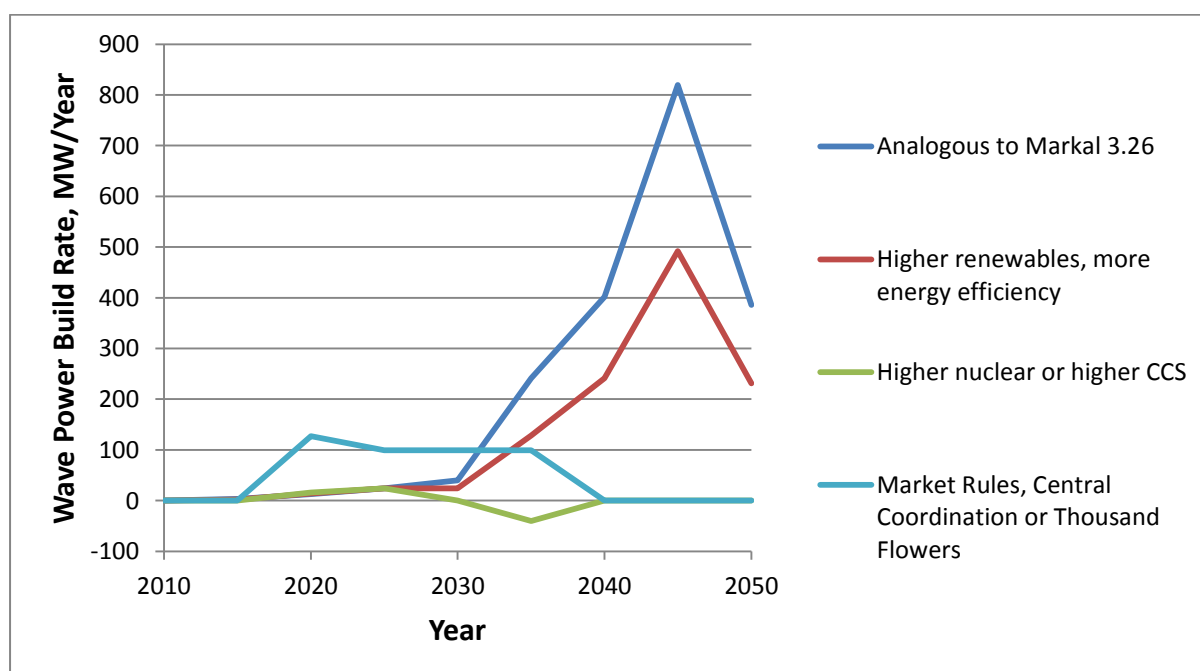


Figure 6.12. Annual build rates (MW/year) for wave power to 2050 in the MARKAL, DECC and Transition Pathways

The government's priority actions for all marine energy systems are managing the risk and costs of RD&D, securing investment for commercial deployment, developing supply chain infrastructure and ensuring planning and consenting.

6.7. Biomass

In each of the DECC scenarios, the biomass power station level is fixed at 0.6 GW capacity in the form of co-fired power stations up to 2030 followed by dedicated biomass combustion. Biomass is also present in combined heat and power stations but without clearly defined inputs or capacities. In the Transition Pathways, biomass is largely used in community CHP plant, with around 10 GW of biogas combined heat and power (CHP) co-generation by 2050 in the *Market Rules* and *Central Co-ordination* pathways, compared to over 52 GW of biogas CHP in the *Thousand Flowers* pathway. This represents the most significant difference between any of the scenarios. This biogas CHP (community scale and micro-CHP) meets around 63% of home and commercial heating demand in the *Thousand Flowers* pathway, providing 112 TWh of distributed electricity generation. Assuming a low electrical capacity factor of 30% for home and commercial CHP, together with industrial renewable CHP, this corresponds to 52 GW of installed CHP capacity by 2050. The availability of the supply of biomass needed to meet this capacity requires further investigation.

Until recently, there has been little policy support available for CHP in the UK, but the Renewable Heat Incentive, which has been in place for non-domestic properties from 2011 and will be in place for domestic properties from 2014, includes support for renewable micro-CHP. The UK government is also supporting work in a number of large UK cities to determine the potential for community-scale heat networks.

7. Greenhouse gas emissions projections for the Transition Pathways

This paper seeks to compare the features of the set of transition pathways for a UK low carbon electricity system to 2050 (Hammond and Pearson, 2013; Foxon, 2013) with those of the DECC scenarios for meeting the 80% greenhouse gas emissions reduction target by 2050. The previous sections have compared the electricity demand, supply and technology penetration projections between these pathways and scenarios. This section examines the resulting projections for greenhouse gas emissions. As the MARKAL and DECC scenarios achieve an 80% reduction for the whole UK economy, it is difficult to make a direct comparison with the transition pathways that only cover the electricity sector. However, the calculations in the DECC 2050 calculator suggest that, for the MARKAL and DECC scenarios to reach the 80% target for the economy as a whole by 2050, the remaining CO₂ emissions from fuel combustion need to be almost completely cancelled out by capture and storage of emissions and by presumed 'negative emissions' associated with the use of bioenergy with CCS.

All three transition pathways have been evaluated in terms of their life-cycle energy and environmental performance within a wider sustainability framework. An integrated approach was used to assess the impact of these pathways, employing both energy analysis and environmental life-cycle assessment (LCA), applied on a whole systems basis: from 'cradle-to-gate'. This analysis examined and accounted for all upstream and operational activities right through to the point of delivery to the consumer, as described in (Hammond *et al.*, 2013).

Climate change, measured in greenhouse gas (GHG) emissions (CO_{2e}), is one of 18 environmental impacts examined as part of this life-cycle assessment of the UK electricity supply industry (ESI) for these three high electric low carbon futures. All upstream and operational activities have been examined and the resulting GHG emission quantified. Projected 'whole systems' GHG emissions for the UK ESI (both upstream and operational emissions) can be seen here in figure 7.1. Additionally, 'whole systems' GHG emissions per kWh (gCO_{2e}/kWh_e) of electricity produced are illustrated in figure 2. Similar trends were seen by (Hammond *et al.*, 2013) relating to *version 1.1* of the pathways, although with less decarbonisation achieved by 2050. These present results relate to most recent *version 2.1* of the pathways.

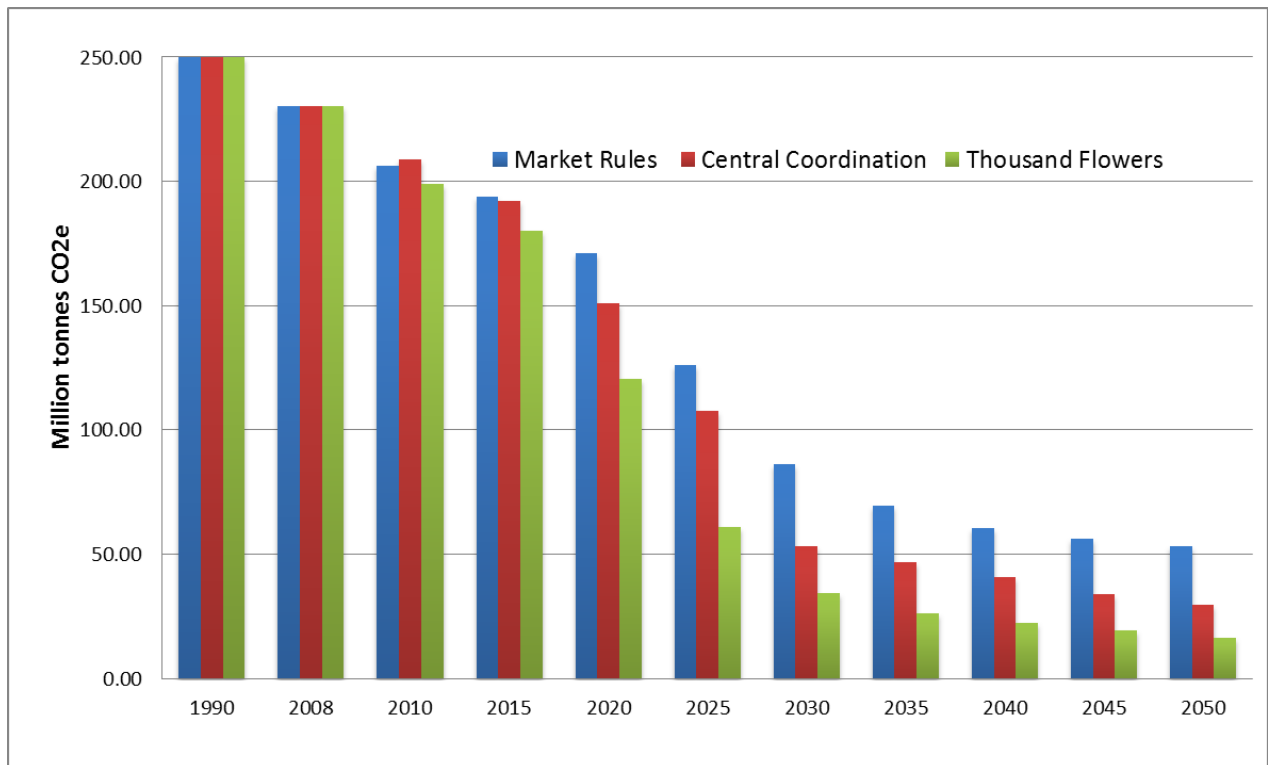


Figure 7.1- Projected UK 'Whole Systems' GHG Emissions for the Electricity Sector (MtCO₂e) 1990-2050 under the Three Transition pathways [Source: (Hammond G P & O'Grady Á, 2013)]

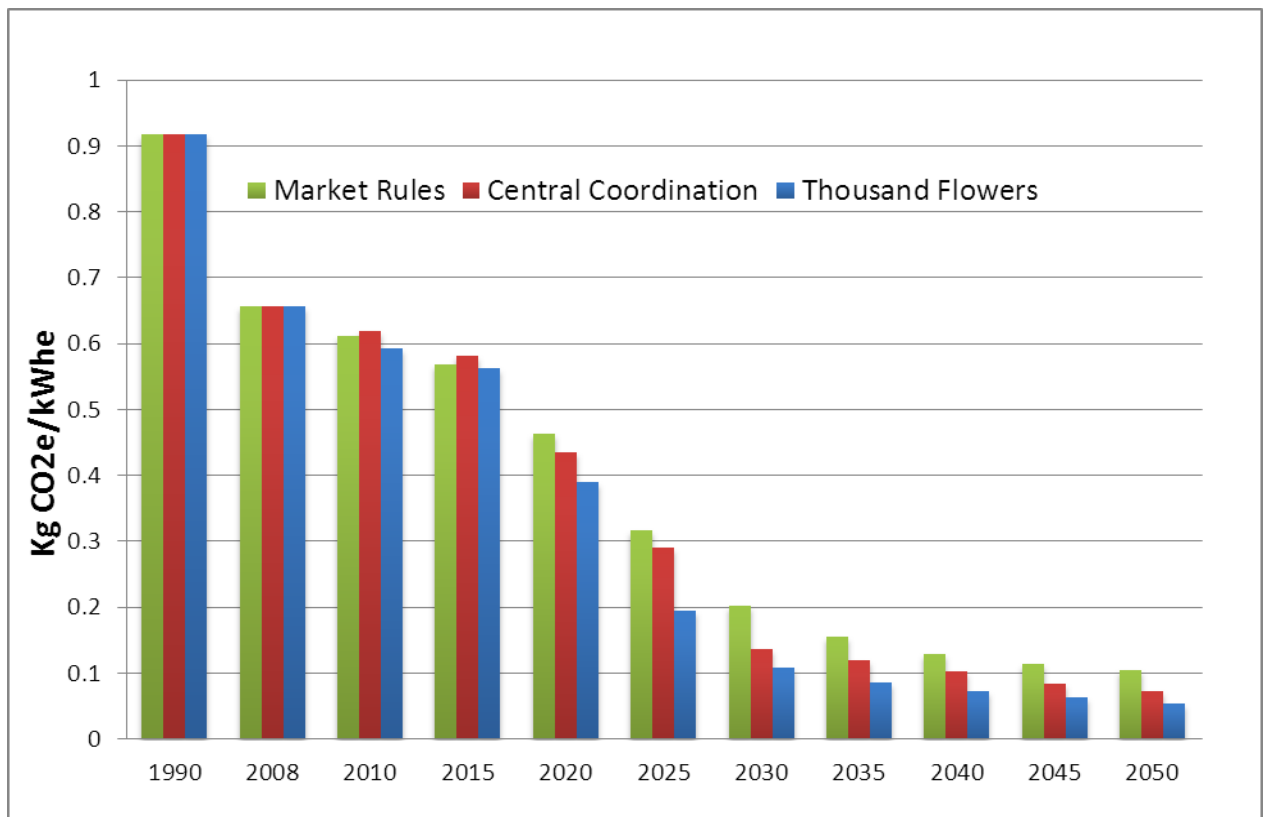


Figure 7.2- Projected 'Whole Systems' GHG Emissions per kWh (gCO₂e/kWh_e) 1990-2050 under all Three Transition Pathways

Since the UK's 80% emissions reduction target only relates to territorial emissions within the UK, the direct (stack) emissions were also projected for all three pathways. These emissions are the result of direct operational activities only, i.e. fuel burned on site of the power generator. Therefore all upstream activities associated have been excluded, making direct emissions the primary focus. All direct GHG emissions projected for the UK ESI is shown in figure 7.3. While the direct GHG emissions projected per kWh of electricity is shown in figure 7.4.

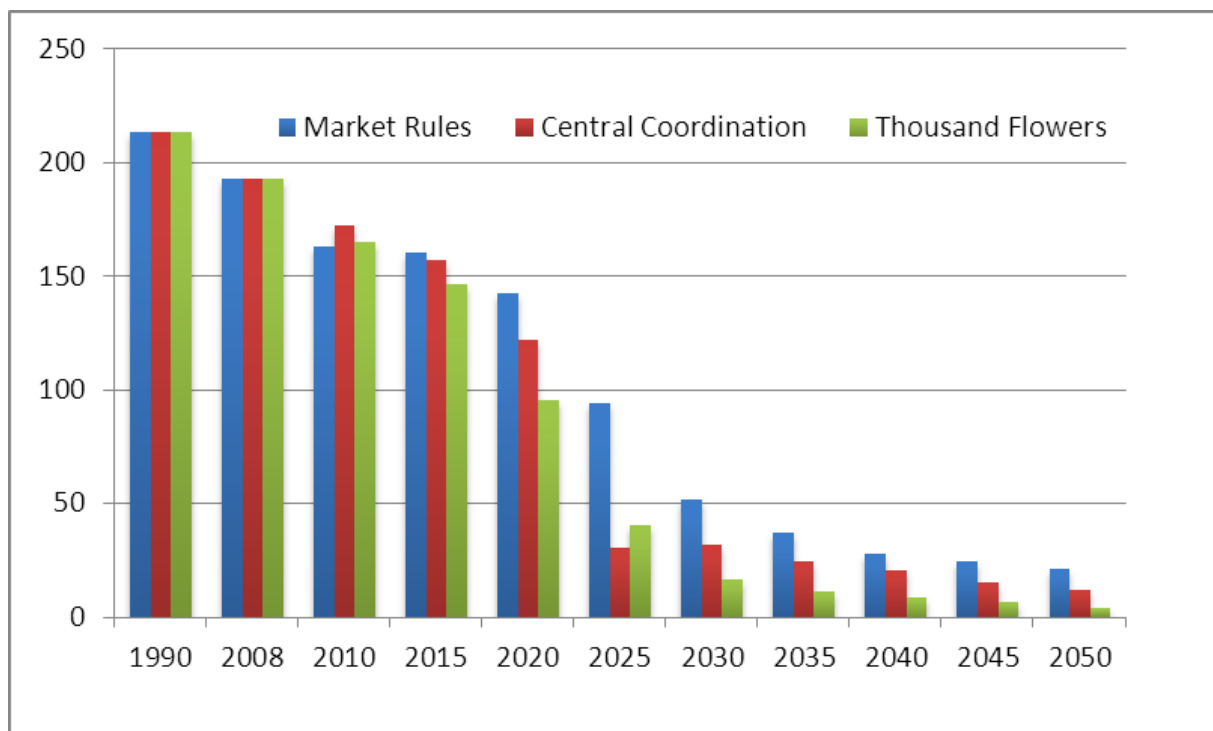


Figure 7.3-Projected UK Direct Emissions from the Electricity Sector (Mt CO_{2e}) 1990-2050 under the three pathways

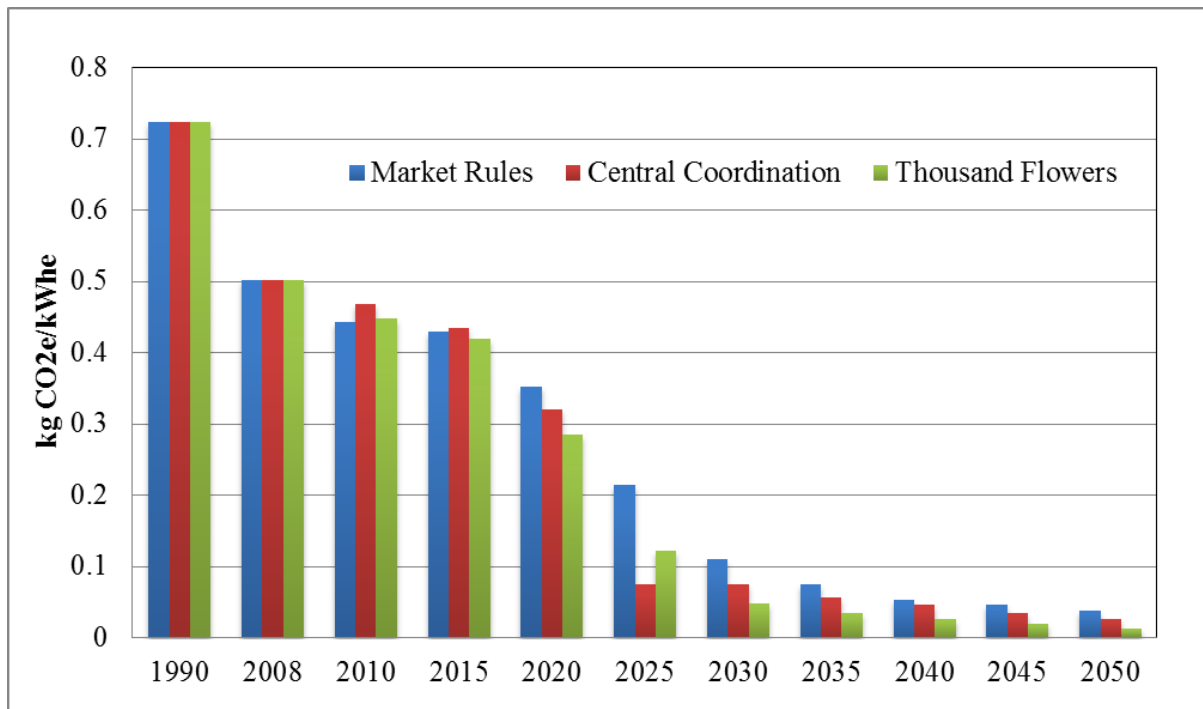


Figure 7.4 - Projected Direct GHG Emissions per kWh (gCO_{2e}/kWh_e) 1990-2050 under all Three Transition Pathways

Clearly, by comparing figure 7.1 and 7.3, and figure 7.2 and 7.4, it can easily be determined that upstream emissions have a significant impact on the environmental performance of the electricity grid mix in all three pathways. The carbon intensities (gCO_{2e}/kWh_e) of the three pathways are significantly increased when upstream emissions are included, resulting in a third more emissions in 2008, and over three times the emissions for thousand flowers pathway in 2050.

According to this analysis, the UK ESI was estimated to emit 230 million tonnes of GHG emissions in 2008 on a whole systems basis. The grid mix has a carbon intensity of 656 gCO_{2e}/kWh_e, although again this can be seen to be much lower on an operational basis only.

Under the *Market Rules* pathway, 'whole systems' emissions from the UK ESI are likely to only fall, accounting for upstream emissions, to around 105 gCO_{2e}/kWh_e by 2050. In contrast, accounting for operational emissions only, GHG emissions are likely to fall to around 37 gCO_{2e}/kWh_e by 2050. Under the *Central Coordination* pathway, 'whole systems' emissions from the UK ESI are likely to only fall to around 73 gCO_{2e}/kWh_e by 2050, whereas, direct emissions were projected to fall to 27gCO_{2e}/kWh_e by 2050. The *Thousand Flowers* pathway was projected to have the lowest emissions, with 'whole systems' GHG emissions of around 53 gCO_{2e}/kWh_e by 2050, and direct GHG emissions of 12 gCO_{2e}/kWh_e by 2050. The large discrepancy between these figures is largely due to the dependence of the pathways on coal and gas CCS, and in particular, the high upstream emissions associated with these technologies (Hammond G P & O'Grady Á, 2013).

The Committee on Climate Change (CCC) has advocated deep cuts in power sector operational emissions through the 2020s (CCC, 2010), with UK electricity generation largely decarbonised by 2030-2040. In contrast, the present transition pathways (see again figure

7.1 and 7.2) projections indicate that the UK ESI could not be fully decarbonised by 2050 on the 'whole systems' basis employed in the analysis. The disparity in these results is largely due to both CCC and Department of Energy and Climate Change (DECC) currently not taking account of upstream emissions. However, even only considering direct GHG emission of the pathways, only the *Thousand Flowers* pathway was projected to achieve almost complete decarbonisation of the electricity sector by 2050 (see figure 7.4).

The Transition Pathways thus illustrate the stringent challenge facing the ESI in order to bear its share of the overall 80% carbon reduction target by 2050. The CCC analysis suggests that optimal pathways to reach this target would require average operational emissions from generation to fall to around 50gCO_{2e}/kWh_e by 2030 (CCC, 2010). Of the three pathways, only the *Thousand Flowers* pathway is projected to reach this target, with GHG emissions falling to 49 gCO_{2e}/kWh_e by 2030. In contrast, the *Market Rules* and *Central Coordination* pathways indicates, accounting for direct emissions only, falling to around 109 gCO_{2e}/kWh_e and 74 gCO_{2e}/kWh_e respectively by 2030 (Figure 7.4).

8. Conclusions

This review has shown the challenges facing the realisation of any of these scenarios or pathways in relation to the rates of deployment of some or all of the available low carbon electricity generation options. As discussed in detail elsewhere (Barton et al., 2013; Foxon, 2013), faster progress in restraining electricity demand, through technological or behavioural energy efficiency measures, will reduce the levels of generation deployment needed. The Transition Pathways have been shown to have levels of deployment broadly comparable to those in the DECC scenarios, though with rates of renewable deployment in the *Market Rules* pathway falling between those of the core MARKAL scenario and the 'higher renewables, more energy efficiency' scenario. The *Central Co-ordination* and *Thousand Flowers* pathways have lower levels of electricity demand than the DECC pathways, due to greater energy efficiency improvements, though they have higher installed capacities, due to the greater proportion of renewable generation with lower capacity factors. The most significant difference is the high level of renewable CHP (both community scale and micro-CHP) in the *Thousand Flowers* pathway. This reduces the amount of centralised generation needed to meet electric heating demand, as well as the power generated by this form of distributed generation significantly offsetting the level of centralised generation needed in this pathway. Given this potential for reducing the level of centralised generation needed, the project team will be further investigating the technical feasibility and social acceptability of renewable CHP in the context of the other projections in the *Thousand Flowers* pathway in future work.

Further work is ongoing to complete an economic analysis of the pathways, as well as systematically addressing a large number of possible, different scenarios through energy-economics-environment modelling (Trutnevyte and Strachan, 2013). Further work is also being undertaken to compare the models being used in the project in order to facilitate interdisciplinary learning ((Trutnevyte, 2013).

This comparison exercise highlights the fact that significantly different technological pathways to a low carbon electricity system in the UK by 2050 are possible. These imply different levels of efforts and different patterns of risks and uncertainties, in relation to energy efficiency and behavioural changes and in technology choices and deployment challenges. How these are addressed and resolved will depend on the governance arrangements of the transition including policy measures and regulatory frameworks, and so, as discussed in more detail elsewhere (Foxon, 2013; Bolton and Foxon, 2013; Foxon and Pearson, 2013), the roles and choices of government, market and civil society actors are crucial to realising any of these pathways.

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